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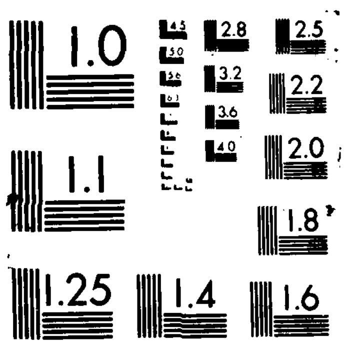
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RESOURCES, CONFUSIONS, AND COMPATIBILITY IN DUAL AXIS TRACKING:
DISPLAYS, CONTROLS, AND DYNAMICS

BY

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THESIS

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RESOURCES, CONFUSIONS, AND COMPATIBILITY IN DUAL AXIS TRACKING: DISPLAYS, CONTROLS, AND DYNAMICS

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University of Illinois at Urbana-Champaign, 1987
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Dual axis compensatory tracking was investigated as a function of whether error displays were integrated or separated, whether axis controls were integrated into one stick or remained separate, and whether the control dynamics on the two axes were the same or different. Tracking error increased and control activity decreased as a function of the summed difficulty of the two control dynamics. Integrated displays and integrated controls both led to increased confusions between tracking axes although error was unaffected. Importantly, performance was also affected by whether the integrality of displays matched that of controls. These results suggest that dual axis tracking is subject to separate effects of resource competition, confusions, and Wickens' compatibility of proximity principle.

ACKNOWLEDGEMENTS

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INTRODUCTION

As technology grows ever more complex, there is a danger that human operators will be pushed beyond the limits of their abilities to maintain safe and effective system operation. No where is this danger more evident than in aviation, especially military aviation. For example, the modern fighter pilot must supervise or control his aircraft's flight control, navigation, communication, threat identification, target acquisition, weapons delivery, and electronic countermeasure systems--all at the same time, perhaps even as his life is immediately threatened.

Of central concern in aviation is the problem of multi-axis control. For example, helicopter pilots must guide their vehicle through all three spatial dimensions of translation and must contend with the rotational dimension as well. Because all axes of motion must be controlled simultaneously, aircraft control systems should be designed to enhance the pilot's ability to control multiple axes at once. The United States Army has been especially interested in whether the two hand controllers currently used in helicopters (the collective and cyclic) should be combined into a single integrated side-arm controller (Harworth, Bivens, & Shively, 1986; Hemingway, 1984).

Whether multi-axis controls should be integrated into a single controller may depend upon whether displays for each axis are also integrated, and whether the control dynamics with respect to each axis are the same or different. Thus, three primary issues may be identified: (1) whether the controls for each axis should be integrated into a single control, (2) whether displays for the several axes should then also be integrated into a single display with a single object representing the aircraft's motion in each axis, and (3) whether the answers to the first two questions depend upon the control dynamics of the aircraft along each axis.

The purpose of the present paper is to review the existing psychological literature pertaining to these three issues and to report the results of a new experiment. Because theory is needed to generalize beyond experimental findings to applications in practical settings, the review will evaluate empirical findings from three theoretical perspectives: attentional resource theory, signal confusion theory, and Wickens' (1986c) compatibility of proximity hypothesis. During the course of the review, it will become clear that some important questions still remain unanswered. These questions will provide the background for a new experiment that will then be reported.

Theoretical Perspectives:
Resources, Confusions, and Compatibility

Whether human performance in dual axis tracking is enhanced or degraded by various configurations of displays, controls, and control dynamics is an empirical question. Yet some theoretical perspective is needed to permit generalization from usually abstract experimental tasks to the concrete "real world" tasks of interest. Three candidates for that perspective are considered here: attentional resource theory (e.g., Gopher & Navon, 1979; Kahneman, 1973; Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, 1980, 1984a,b, 1987a,b), confusions theory (e.g., Duncan, 1979; Hirst & Kalmar, 1987; Klapp et al., 1985; Levison & Elkind, 1967; Navon & Miller, 1986), and Wickens' (1986c) compatibility of proximity hypothesis.

Attentional Resource Theory

Concepts of a limited attentional capacity began appearing in the psychological literature during the decade of the 1960's (e.g., Chernikoff, Duey, & Taylor, 1960; Moray, 1967). From those early hypotheses, there developed several sophisticated theories all of which assumed that task performance could be related to the task's demand for processing resources (e.g., Friedman, Polson, Dafoe, & Gaskill, 1982; Kahneman, 1973, Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens, 1980, 1984b). When multiple tasks are performed together, therefore, the decrements in their performance should be predictable from their summed resource demand.

This prediction of resource theory can account for data from a large number of experiments (for reviews, see Kahneman, 1973; Navon & Gopher, 1979; Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977; Wickens, 1984a,b). Consequently, resource theory has gained widespread acceptance even though the issue of whether resources exist is still a matter of discussion in the literature (Gopher, 1986; Hirst & Kalmar, 1987; Navon & Miller, in press; Wickens, 1986a). Further, it should be noted that some capacity theorists have posited a single resource drawn upon by all tasks (e.g., Kahneman, 1973; Kantowitz, 1985) while others have argued for several independent resources (e.g., Friedman et al., 1982; Navon & Gopher, 1979; Wickens, 1980, 1984a,b). In the present study, however, the issue of one or multiple resources will not come up and so will not be addressed.

An issue that will be addressed is an important distinction proposed here between "strong" and "weak" resource theorists. Both groups of theorists agree that performance is a function of the <u>scarcity</u> of resources; the two groups are to be differentiated only by what they have in mind when they use the term "resources". This distinction between strong and weak theories is important because, as will become clear, the conditions sufficient to establish resource competition are defined differently by the two groups.

Strong resource theorists have followed Kahneman (1973) in defining a resource as energy to be distinguished from the processing structures to which such energy might be allocated (e.g., Friedman et al., 1982; Herdman & Friedman, 1985; Gopher & Navon, 1979; Kantowitz, 1985; Navon & Gopher, 1979; cf., Navon, 1984). Thus, in order to show that tasks compete for a common pool of energy rather than just common processing structures, strong theorists maintain that two conditions must be met. First, it must be the case that the resource demand of the two tasks together can reasonably be assumed to exceed the total amount available. Second, instructions to allocate attention away from one task to another by varying degrees must result in corresponding changes in how well the two tasks are performed (cf., Norman & Bobrow, 1975; Wickens, 1984b).

Weak resource or demand theorists, on the other hand, have followed Norman & Bobrow (1975) in allowing a resource to include the entire set of processing structures and sources of energy used by a task or task component. Gopher (1986) was clear in this regard when he wrote that "the definition of resources as proposed here...includes both structural and energetical components" (p. 356). Wickens (1984b) espoused a similar position, when in the context of a multiple resource model, he defined resources as whatever "categorical distinctions [between tasks]...account for the greatest variance in time-sharing efficiency" (p. 91, brackets added), and again when he observed that "very rapid intertask (or interchannel) switching may, for all intents and purposes, be labeled as shared resources" (p. 87).

As a result of their broad definition of the term "resource", demand theorists are willing to accept a more lenient criterion for showing that two tasks (or task components) share a common resource. As with the strong theorists, the assumption that the summed demand of both tasks exceeds the total supply of a given resource must be reasonable. But because there is no need to distinguish energy from processing structures, the second condition proposed by the strong theorists is not regarded as necessary (though it is sufficient). Instead, demand theorists require only that the quality of performance in one task can be shown to decrease with the increasing demand of a loading task.

In the present study, demand theory rather than the strong version of resource theory is what is examined. Although Kantowitz (1985) has described demand theory as uninteresting, Navon (1984) has argued persuasively that energy can not be distinguished empirically from processing structures after all. Thus, he concludes that strong resource theory is untestable. Further, demand theory is not uninteresting if the alternatives to it deny the primacy of demand or scarcity in multiple task performance. One such alternative has recently been offered and will now be considered.

Confusion Theory

Navon (1985; Navon & Miller, in press) has proposed that dual task decrements in performance can be understood entirely without reference to the demand construct. Instead, he suggests that such decrements can be accounted for by a variety of intertask confusions which he generically labels "outcome conflicts". Further, Navon & Miller (in press) suggest how outcome conflicts may account for data from a number of experiments traditionally taken to support demand theory (e.g., Allport, Antonis, & Reynolds, 1972; Baddely, Grant, Wright, & Thompson, 1975; Friedman & Polson, 1981; Friedman et al., 1982; Treisman & Davies, 1973). Other theorists, such as Hirst and Kalmar (1987), have made similar arguments.

Like Navon, Hirst and Kalmar (1987) offer confusions as an alternative to resource competition in accounting for decrements in the simultaneous performance of two tasks. Their basic approach was to show that dual task interference could arise from an increase in the similarity between tasks along a variety of different dimensions. This demonstration, they argued, discredited resource theory as unparsimonious since the only way resource theory could accomodate their data was by postulating a separate resource for each dimension of similarity. Further, the fact that interference was directly linked to similarity implies that confusions underlie interference, although the confusions themselves may be difficult to document.

Hirst and Kalmar's argument is fundamentally an argument of reasonableness. Their conclusion is that resource theory is unreasonable, and therefore should be rejected in favor of a theory based on confusions. But resource theory may be unreasonable only if it attempts to account for all task interference effects without reference to other potential mechanisms of interference. Indeed, confusions theory may also prove to be unreasonable if it likewise ignores all other potential underlying mechanisms of interference. Evidence that confusions theory alone may be inadequate as the sole mechanism of task interference seems apparent from Navon and Miller (in press).

Navon and Miller reported the results of two experiments both of which seemed to document the occurence of outcome conflicts. Both experiments required subjects to search for one type of target in one channel and another type of target in a second channel. Subjects' reaction times were significantly delayed when non-targets in one of the channels were in the same category as targets in the other. But, as the authors themselves noted about their first experiment, "although a considerable outcome conflict was certainly demonstrated, it still does not account for the large single- to dual-task decrement that has been observed here" (p. 8). The authors attributed the large dual task decrement to a task switching strategy employed by subjects to cope with the high difficulty of the tasks involved, although they offered no evidence for such switching. In an effort to prevent subjects from adopting such a strategy, the authors ran a second experiment using much simpler tasks but still found large dual task decrements with only weak evidence for confusions.

Although the data reported suggest that confusions can only partially account for dual task decrements, Navon and Miller come to the conclusion that confusions can account for dual task decrements in general without reference to the resource construct. Their reasoning seems to be that since confusions are known to occur and resources are not known to exist, it is most parsimonious to assume that there are other kinds of confusions that do account for the entire dual task decrement. Evidence that this is their reasoning is found in the following excerpt:

> There might also be other sources of conflict that were responsible for some or all of the residual task interference that was not accounted for by the factors we manipulated.... It is obvious why such conflict...is impossible to substantiate definitely in our design, as well as in most other dual task paradigms: It may occur in all conditions. (p. 7)

In spite of Navon and Miller's assertions, the results they report are congruent with resource theory if one allows for the occurrence of intertask confusions. Once subjects recognize the occurence of confusions, they may pursue one of two strategies. One strategy would be to simply let the confusions manifest themselves as errors. The other would be to attempt to inhibit confusions by invoking some sort of filtering mechanism. Such a mechanism would be resource consuming, however. Thus, if two high demand tasks use up nearly all of the available capacity, there might not be a sufficient residual available for the filter to work efficiently.

In Navon and Miller's first experiment with the two difficult tasks, resource competition is high which leaves insufficient resources available for the filter. Thus, both resource competition and confusions contribute to the overall decrement. In the second experiment with the easier tasks, resource competition is lower so that the filter is more efficient. As a result, few confusions are in evidence but there is still a dual task decrement due to the total demand placed on processing resources by the two tasks and the filter.

Inclusion of confusions along with resources in a general model of dual task interference would seem to be an important step forward and has recently been proposed by Wickens (1986a, 1987a,b; cf., Duncan, 1979; Garner & Morton, 1969). Besides enlarging psychologists' present understanding of complex task performance, such inclusion would provide an important link to other areas of psychology where the construct of confusions has traditionally played an important role, especially learning and memory (Anderson, 1974, 1985; Battig, 1968; Birnbaum, 1968; Conrad, 1964; Fracker, 1980; Glenberg, 1976; Goggin & Martin, 1970; Lintern, in preparation; Lewis & Anderson, 1976; Martin, 1968; Martin, 1972; Mueller, Gautt, & Evans, 1974; Osgood, 1949; Pozella & Martin, 1973; Postman, 1975; Shulman, 1972).

In addition, a well defined model of the role of confusions in human performance may help to account for data currently inexplicable by resource theory. For example, multiple resource theory predicts that multiple task performance should deteriorate as tasks increase in similarity along certain dimensions (Wickens, 1984b). Yet several studies have found just the opposite effect comparing similar and dissimilar tapping rhythms (Klapp, 1979, 1981; Klapp, Hill, Tyler, Martin, Jagacinski, & Jones, 1985), identical and dissimilar control dynamics in dual axis tracking (Chernikoff, Duey, & Taylor, 1960), similar and dissimilar stimulus-response mappings in choice reaction time (Duncan, 1979), and similar and dissimilar timing parameters in ballistic hand movements (Kelso, Southard, and Goodman, 1979).

Whether confusions theory could account for these data is another question. If confusions simply increase with increasing task similarity as Navon & Miller (1986) suggest, then probably not. But if confusions are some function of the incompatibility of task requirements (cf., Chernikoff & Lemay, 1963; Klapp et al., 1985; Kramer, Wickens, & Donchin, 1985; Wickens, 1987a,b), then confusions may account for such data.

At this point in time, however, such notions are speculative. Data documenting the occurence of confusions is needed. Only after confusions have been documented across a wide variety of task combinations will it be possible to construct a model of when and how they arise.

Compatibility of Proximity

Transcending issues of both demand and confusions theory, Wickens' (1986c) compatibility of proximity hypothesis holds that complex tasks can be located in a multidimensional space where each dimension represents the "proximity" of specific task elements. For example, one dimension may reference the degree to which information displays are integrated into a single object or are presented separately. Another dimension may indicate the degree to which subjects must integrate the two information sources in order to select an appropriate response. The essence of the hypothesis is that the quality of performance will improve as the proximity of task elements with respect to one dimension tends to match that with respect to every other dimension.

Wickens' (1986c) has summarized a number of experiments which have tended to support the compatibility of proximity hypothesis (Barnett & Wickens, in press; Boles & Wickens, in press; Carswell & Wickens, in press; Casey & Wickens, 1986; Goettl, Kramer, & Wickens, 1986; Wickens et al., 1985). In addition, he has shown that the hypothesis provides a framework capable of subsuming work from earlier theorists (e.g., Garner, 1974; Kahneman & Henik, 1981; Lappin, 1967; Pomerantz, 1981). He has also shown that the hypothesis more precisely defines the limits of phenomena reported by other researchers. To cite just one example, the hypothesis suggests that the benefit of integrated object displays discussed by Kahneman & Henik (1981) may be enhanced if the displayed information must be integrated, but may be attenuated if the displayed information is to be treated independently--a prediction verified by Wickens and his associates (Carswell & Wickens, in press; Casey & Wickens, 1986). Thus, although the mechanism underlying such compatibility of proximity effects is unknown, the phenomenon appears to be strongly established in the empirical literature.

While compatibility of proximity appears to conceptually different from notions of resource competition and outcome conflicts, it may not always be possible to empirically distinguish one mechanism from the other. One task domain in which such distinctions apparently can be made is dual axis manual control. It is to this domain that the focus of present paper now turns.

Dual Axis Tracking: Displays, Controls, and the Heterogeneity of Control Dynamics

Resource demand, confusions, and compatibility seem to represent different mechanisms potentially underlying effects of display, control, and control order configurations on the quality of tracking performance. The potential contributions (or "predictions") of these three mechanisms will be discussed in two sections. First, predictions regarding the heterogeneity of dynamics will be treated. Then, predictions about the effects of display and of control integrality will be presented. Both sections will address the logic underlying the predictions and then will review the dual axis tracking literature relevant to those predictions. As will be seen, clear tests distinguishing among the three mechanisms have not yet appeared in the dual axis tracking literature.

Because the focus of the present study is on how demand, confusions, and compatibility contribute to the role of displays, controls, and dynamics in dual axis tracking, only relevant portions of the tracking literature are reviewed. Specifically omitted from the review are those studies which have addressed the more general issue of axis independence in dual axis tracking (e.g., Adams & Webber, 1961; Bilodeau, 1955, 1957; Bilodeau & Bilodeau, 1954; Ellson, 1947; Gopher & Navon, 1979; Hoppe, 1974; Navon, Gopher, Chillag, & Spitz, 1984). Nevertheless, the conclusions of the present study may have implications for the general question of axis independence.

Heterogeneity of Control Dynamics

Predictions. When the control dynamics differ on the two axes of a dual axis tracking task, resource theory suggests that tracking error should be a function of the total demand imposed by the two axes together. Suppose, for example, that one group of subjects tracked with zero order (position control) dynamics on one axis and second order (acceleration control) dynamics on the other (the heterogeneous condition), a second group tracked with zero order dynamics on both axes, and a third group tracked with second order dynamics on both axes.

Second order tracking is known to be more demanding than zero order as well as first order (velocity control) tracking as measured by subjects' open loop gain, effective time delay, remnant, and subjective workload ratings (Baty, 1971; Kelly, 1968; McRuer & Jex, 1967; Navon & Gopher, 1980; Wickens, 1984a; Wickens, 1986b; Wickens & Derrick, 1981; Ziegler, 1968). This increased demand seems to result from the need to generate phase lead in second order tracking (McRuer & Jex, 1967; Wickens, 1986b) which in turn requires subjects to perceive the acceleration of the error display, a type of perception for which humans are poorly suited (Wickens, 1984a).

Therefore, according to demand theory, zero order tracking error should be greater in the heterogeneous dynamics condition, but tracking error in the second order axis should be greater in the homogeneous condition (i.e., when paired with another second order axis). These differences in tracking error ought to be accompanied by differences in control gain.

Control gain may index the degree of either subject caution or control effort. If control effort is assumed to be constant within a given control order, then as subjects become more cautious, their open loop gain should decrease. Competition from a secondary task results in such decreases in gain, presumably because of the increased demand on processing capacity (Baty, 1971; Levison, Elkind, & Ward, 1971; Watson, 1972; Damos & Wickens, 1980; Wickens, 1976; Wickens, 1986b; Wickens & Gopher, 1977). Thus, second order gain should be greater and zero order gain should be less under heterogeneous dynamics than under homogeneous control dynamics.

Confusions theory, on the other hand, would predict that tracking error would be greater under heterogeneous dynamics for both zero and second order control. The reason is that subjects in the heterogeneous group must generate two incompatible transfer functions: one in which they generate lead in response to the second order axis, and one in which they generate lag in response to the zero order axis (McRuer & Jex, 1967; Wickens, 1986b).

In the language of the optimal control model (Levison, 1982), heterogeneous subjects must maintain two incompatible mental models of axis control dynamics while homogeneous subjects need maintain only one model. This incompatibility between mental models (or atheoretically, between transfer functions) could lead to two different--but not mutually exclusive--outcomes. First, what might be called control order confusions may be manifest in the open loop transfer functions of the heterogeneous group. Second, heterogeneous subjects may decrease their open loop gain as they attempt to avoid such confusions.

The compatibility of proximity hypothesis predicts an interaction of the heterogeneity of dynamics with both display and control integrality. Therefore, discussion of those predictions is deferred to the section on display and control integrality.

Experimental results. Only a handful of studies have reported data that might test the discrepant predictions of demand and confusions theory (Chernikoff, Duey, & Taylor, 1960; Chernikoff & Lemay, 1963; Levison & Elkind, 1966, 1967; Miller, Jagacinski, Navalade, & Johnson, 1982; Wempe & Baty, 1968). Levison & Elkind (1966, 1967) showed that control order confusions do indeed occur but only in one direction: subjects' open loop response to the zero order axis took on characteristics of the that to the second order axis. Wempe & Baty (1968) showed that tracking transinformation rates were lower given dissimilar rather than similar control dynamics.

From the standpoint of the present hypothesis, the two most cited studies are those of Chernikoff and his colleagues (Chernikoff et al., 1960; Chernikoff & Lemay, 1963). Both studies have demonstrated that both zero and second order tracking error is worse under heterogeneous conditions; they did not obtain subjects' open loop describing functions, however. (Chernikoff et al. (1960) demonstrated the same effect between zero and first order dynamics as well as between first and second order dynamics.) One may question, though, why both zero and second order error would increase if control order confusions are asymmetric. Should not error increase only in the axis where confusions are evident if such confusions alone accounted for the increase in error?

To answer this question, note that such an asymmetry is unavoidable given that control order confusions occur at all. This is because a lead generating open loop response to a zero order plant would still result in an overall stable system (at least up to the point where the subject's responses began adding to rather than subtracting from the error, probably near or perhaps beyond the upper limit of the input bandwidth; see McRuer, 1980; Wickens, 1986b); but a lag generating response (appropriate for a zero order system) to a second order plant would quickly cause the overall system to become unstable. Consequently, if control order confusions are bi-directional, subjects would have to suppress those from the zero order to the second order axis. If suppressing such confusions leads subjects to track more cautiously, then they may attenuate their open loop gain. Because lead generation in the zero order task and gain attenuation in the second order task could both lead to increases in error relative to tracking under homogeneous dynamics, control order confusions could account for the data of Chernikoff and his associates.

Even though control order confusions may account for the above data, it is not clear that the data contradict demand theory. In both of the Chernikoff studies, relatively simple disturbance functions were used. In the 1960 study, subjects tracked a single sinusoid (.032 hz) in the horizontal axis and a single sinusoid (.053 hz) in the vertical axis. As a result, the time courses of the two errors were easily predictable.

Tracking in the 1963 experiment was only slightly more difficult where the input to both axes was the sum of two sinusoids (.048 and .078 hz) although the two axis signals were 90 degrees out of phase. Further, the authors do not say whether the phases of the two sinusoids within a signal were varied across trials, leaving the reader to presume that they were not. Thus, the time courses of error in both experiments seem to have been easily predictable, and hence easily learned by the subjects (cf., Krendel & McRuer, 1968; Pew, 1974; Poulton, 1957; Wickens, 1984a).

The use of these simple disturbance functions and the ability of human subjects to detect and shadow the periodicity in them (especially at low frequencies; see Pew, 1974) suggests that the overall demand on subjects' processing resources may have been low. But Norman and Bobrow (1975) have shown that increased resource demand can lead to a performance decrement only if total demand exhausts the resource supply. Since it appears questionable whether this requirement was met in the Chernikoff studies, those data should not be taken as a fair test of demand theory.

Finally, at least one study has reported results clearly inconsistent with confusions theory. Miller, Jagacinski, Navalade, and Johnson (1982) had subjects perform a single axis compensatory target acquisition task with two control sticks. In one condition, both sticks controlled the target's velocity. In another condition, one stick controlled the target's velocity (first order dynamics) and the other controlled its position (zero order dynamics). The output of both sticks were combined to control the target's position.

Miller et al. found that target capture times were longer when both sticks controlled velocity rather than when one stick controlled velocity and the other position. This result is notable because it is exactly the opposite of what would be predicted by confusions theory. While the results clearly contradict confusions theory, they do not offer support for demand theory since the authors claim that unpublished experiments also found the heterogeneous combination to be superior to the position-position combination. This result may reflect Braune and Wickens' (1986) suggestion that zero and first order dynamics are roughly equivalent in difficulty. Evidently, the superiority of heterogeneous control in the Miller et al. study reflects some dimension of performance not captured by either confusion or demand theory.

In summary, while it seems that control order confusions can and do occur, it is not clear that they are inevitable. Further, it remains to be seen whether resource demand needs to be included in any account of tracking with heterogeneous dynamics.

Integrality of Displays and of Controls

Predictions. Predictions of demand and confusions theory differ in regard to the main effect of display integrality. (Most versions of demand theory make no obvious predictions about the effect of control integrality on performance. However, Friedman & Polson's (1981) hypothesis of two independent resources corresponding to the two cerebral hemispheres suggests that performance should be superior with separated rather than integrated controls. But, as will be seen, this is the same prediction made by confusions theory.) According to demand theory, tracking error should increase when displays are separated rather than integrated. But according to confusions theory, tracking error should increase with integrated, not separated, displays.

If separate error displays are given for each axis, then there may be frequent instances when both error indicators are not simultaneously within foveal vision. Subjects may then pursue one of two possible strategies. They may visually scan back and forth between axes, looking at the error on one axis and then at the other. Or they may fixate on some point on the display and observe both errors simultaneously through peripheral vision.

A scanning strategy may place a load on memory since subjects must then remember the status of error on a given axis at the time of the last fixation (cf., Allen, Clements, & Jex, 1970; Onstott, 1976). Using peripheral vision will avoid loading memory but will load the perceptual system since perception of the display will then be relatively degraded due to the lower acuity of peripheral vision. Either way, demand should increase and, therefore, so should tracking error (cf., Levison & Elkind, 1967; Levison, Elkind, & Ward, 1971; Wickens, 1986b).

Confusions theory, on the other hand, holds that tracking error should be greatest with whatever type of display leads to the most confusions. Confusions between error signals ought to be greatest whenever it is most difficult to separate one signal from another, presumably when both signals are received through a common channel. If one assumes that visual channels are spatially defined (as in the spot-light metaphor of attention; cf., Briand & Klein, 1987; Ericksen

& Yeh, 1985; Kahneman & Treisman, 1984; Posner, 1980; Posner, Snyder, & Davidson, 1980; Treisman, 1969; Watchel, 1967; Wickens, 1984a), then confusions should be greatest with integrated rather than separated displays. Further, Garner's work (Garner, 1974; Garner & Fefoldy, 1970; cf., Cheng & Pachella, 1984; Pomerantz, 1981) suggests that because the dimensions of an integrated cursor (vertical and horizontal displacement) are integral, a cost in confusions should arise if the two error signals are uncorrelated.

In addition, if response hands are assumed to define separate channels within the human motor system (see Kelso, Southard, & Goodman (1979), Marteniuk & MacKenzie (1980), and Schmidt (1982) for evidence for and against this view), then confusions should also be more likely with integrated rather than separated controls. Thus, confusions theory seems to predict that errors will increase with both integrated displays and integrated controls while demand theory predicts just the opposite for display integrality and is silent on control integrality.

Other effects could moderate the predictions of confusions theory. Scanning between axes, for example, might lead to some confusions given separated displays due to interference effects in memory (see the discussion of scanning above). Similarly, tracking with two hands given separated controls could lead to confusions mediated by incompatible hand movements (Kelso et al., 1979; Peterson, 1965). In any case, confusions theory predicts that, if such confusions can be documented, they will account for whatever interference effects appear in the tracking error measures. (How confusions may be documented is described at the end of this section.)

While demand and confusions theory make different predictions about display and control main effects, they are silent with respect to how display and control integrality will combine with the heterogeneity of dynamics to influence performance. This interaction is addressed by the compatibility of proximity hypothesis, however. Specifically, the hypothesis suggests that tracking error will be less if displays and controls are both integrated or both separated than if one is integrated and the other is separated. A process model of how this interaction between display and control integrality arises is described next.

Consider first a compensatory dual axis tracking display like the one shown in Figure 1 where two orthogonal tracking axes define a two-dimensional plane. In the integrated display, the vertical and horizontal axes errors are represented by a point in the plane. In the separated display, the errors are represented by the projections of this point onto the two axes.

Because the integrated display represents error by means of a single object, people should have difficulty in separating the two errors from each other (Carswell & Wickens, in press; Garner, 1974; Garner & Fefoldy, 1970; Wickens, 1986c; Woods, Wise, & Hanes, 1981).

Thus, people may be expected to process the radial error which is directly represented by the integrated error indicator. With separate error displays (i.e., the projections of radial error onto the two axes), on the other hand, subjects should have no trouble in perceiving the two errors directly.

But now consider the requirements imposed by whether errors on the two axes are controlled by an integrated control or by two separated controls. Given separated controls, subjects would need separate representations of the two errors. Given an integrated control, subjects could control both errors simultaneously by moving the control stick at various angles, but this strategy amounts to controlling radial error and hence requires a radial representation of error. Consequently, subjects should need a radial representation of error with an integrated control, and separate representations given separate controls.

When the needed representation of error is not directly present in the display, it follows that subjects must generate that representation themselves. That is, subjects with an integrated display but separated controls will need somehow to recover the projections of the radial error onto the vertical and horizontal axes. Similarly, subjects with separated displays but an integrated control should find the intersection of the two errors in the dual axis plane. Both of these processes will be referred to as "mapping operations".

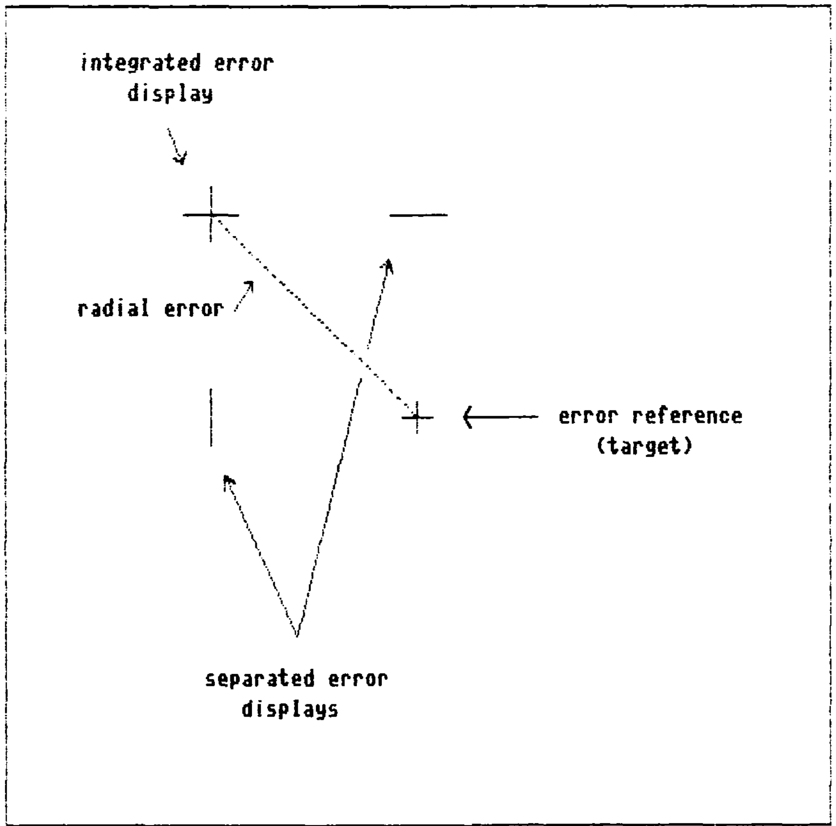

Figure 1. Display for a compensatory dual axis tracking task showing both separated and integrated error cursors. Also shown is the error reference or target. Radial error refers to the distance from the error reference to the integrated error cursor; radial errors can also be defined as the distance between the two separated error cursors. The figure is a scale representation of the display used in the present experiment (see Method).

To the extent that these mapping operations are unsuccessful and confusions result, tracking error should increase when the integrality of displays and controls do not match. But tracking error should also increase to the extent that these mapping operations are resource demanding and compete with the tracking task for processing resources. Thus, both confusions and resource demand may contribute to the same general effect. Further, it should be possible to distinguish the relative contributions of each under certain circumstances.

If mapping operations are successful, there should be no systematic relation between documented confusions and the compatibility of display and control integrality. But if tracking error increases in the absence of confusions, then that increase may be taken as evidence that the mapping operations are resource demanding. If, on the other hand, confusions are absent and error is unaffected, then the resource demand of such mapping operations may be presumed to be minimal.

The latter outcome could also be taken as evidence against the mapping operation construct, however. Fortunately, it is possible to validate the existence of mapping operations in the complete absence of confusion and error effects. From the perspective of mental chronometry (e.g., Posner, 1978), the mapping operation required when the integrality of displays and controls do not match should be detectable as an increase in subjects' effective time delay (cf., Wickens, 1976, 1986). Effective time delay is a control theory measure of the time it takes subjects to process the error signal from the moment it has been perceived to the moment of response execution. (How time delay is computed is described in the Results section.) In addition, subjects may be more cautious as they carry out such mapping operations, and this increased caution should appear as decreases in control gain and control velocity (a measure of the length of control movements per unit time).

If the operations fail, confusions should appear and be detectable as signal cross-coherence. Intuitively, cross-coherence represents control activity in one axis that is linearly related to error in the opposite axis. More formally, coherence is a measure of the linear association between two signals within a given bandwidth and is equivalent to a squared correlation where cases are specific frequencies and observations are the power in those frequencies for the two signals (Dixon et al., 1983). (Mathematically, coherence is the concentration of probability around the least-squares estimate of the linear transformation that maps one signal onto another within a given bandwidth. If the bandwidth contains only one measurable frequency, then the coherence will always be unity.)

Two types of cross-coherence are possible. One, referred to as primary cross-coherence, indexes confusions between axes; it is the coherence between the input signal to one axis and the control output in the other axis. The second type, secondary cross-coherence, is defined only when subjects use separate control sticks which move in orthogonal directions. Secondary cross-coherence indexes confusions as to which control stick controls which axis; it is the coherence between the input signal to one axis and control output in the correct axis but of the wrong control stick. As such, secondary cross-coherence does not directly add error to either axis since it involves control stick displacement along a non-relevant axis.

Besides a display by control integrality interaction, the compatibility of proximity hypothesis also predicts a more complex interaction between display and control integrality and the heterogeneity of dynamics. Specifically, the requirement to adapt to two distinct tracking dynamics should be more easily met when displays and controls are both separated than when either or both are integrated. Similarly, adaptation to the same dynamics on both axes may be enhanced when displays and controls are both integrated rather than when one or both are separated. Note that these predictions imply that displays, controls, and dynamics contribute equally to compatibility. Whether such equality is the case is an empirical question, however: it may be that the importance of the three factors to compatibility are not equal. In any case, incompatible display-control-dynamics configurations should lead to increased error due to either an increase in confusions or to the expenditure of extra effort to avoid confusions.

Experimental results. Unfortunately, few dual axis tracking studies have attempted to document confusions by measuring cross-coherence. Only two studies are known to have collected cross-coherence data: Damos and Wickens (1980) and Tileman (1979). Both studies failed to find any significant evidence for confusions, but both used separated displays and controls. Thus, a serious attempt to document confusions in dual axis tracking as a function of display and control integrality is currently lacking in the literature. Therefore, it is presently possible only to infer the presence or absence of confusions from other measures such as tracking error.

As predicted by demand theory, some studies have shown that separated displays do lead to greater tracking error than do integrated displays (e.g., Bailey, 1958; Chernikoff & Lemay, 1963; Sampson & Elkin, 1965). However, Burke, Gilson, and Jagacinski (1980) found error unaffected by display integrality. One could argue that the scanning decrement associated with separated displays was matched by a decrement due to confusions with integrated displays. But this possibility has yet to be examined.

Although Baty (1971) has provided data suggesting that scanning is what accounts for the cost to separated displays, Burke et al.'s study does not seem to have differed from the others in the need for scanning. But it did differ from Sampson and Elkin's (1965) study in one important way. While Sampson and Elkin used an integrated control in all display conditions, Burke et al. used separated controls. Taken together, these two studies suggest some kind of interaction between display and control integrality.

Further evidence for a display-control interaction may be found in a comparison of experiments by Baty (1971), Bartram, Banerji, Rothwell, and Smith (1985), and Regan (1960) with one reported by Levison, Elkind, and Ward (1971). Levison et al. found that tracking using separated displays was worse with integrated rather than separated controls. Baty, Bartram et al., and Regan, on the other hand, found that tracking using integrated displays was better with an integrated control rather than separated controls.

It is tempting to take these results as rough support for the existence of a compatibility of display and control integrality effect. Unfortunately, the effect is completely absent in a study where it ought to be present. Chernikoff and Lemay (1963) had subjects track in all four conditions needed to test the compatibility of integrality prediction; that is, the complete factorial manipulation of display integrality and control integrality. They reported no evidence for any interaction whatever between display and control integrality.

Although these researchers did not find the predicted display-control interaction, they did find other evidence favoring the compatibility of proximity hypothesis. When control dynamics were the same on both axes, integrated displays led to less tracking error than did separated displays while control integrality had no effect. But when control dynamics differed between the two axes, separated controls led to less error than did an integrated control while display integrality had no effect.

Although these two interactions conform in a descriptive sense to the compatibility of proximity hypothesis, the processes which give rise to them are not entirely clear. Chernikoff and Lemay suggest that separated displays may help subjects avoid confusions between control orders but say little beyond this. Concerning control integrality, they suggest that when heterogeneous dynamics are used, subjects need separate controls to avoid confusions between the required "pattern of response movements" (p. 99). But when homogeneous dynamics are used, confusions between movement patterns do not occur; hence, separated controls offer no benefit.

This reasoning is not entirely convincing, however. Unless the two disturbance functions contain the same frequencies and are in phase with each other, the proper pattern of response movements in one axis will usually be different from that in the other. Consequently, confusions should nearly always be possible and ought to be exacerbated by an integrated control regardless of whether dynamics are the same or different (bearing in mind that separate controls may also lead to confusions--see "predictions" above). It is just this type of interpretative difficulty that may be alleviated by documenting the occurrence of axis confusions with cross-coherence data and control order confusions with a describing function analysis.

If Chernikoff and Lemay's data appear problematical, that may be because of an apparent flaw in their experimental design (besides their failure to use demanding input signals): the same six subjects were used in all 12 of the experimental conditions. Since multiples of 12 subjects are needed to cancel out symmetric carry over effects in an experiment with 12 conditions, and because no within subjects design can cancel out asymmetric effects, such effects can not be ruled out as an explanation for the reported data (cf., Matthews, 1986; Poulton, 1974, 1982; Scheffe, 1959). Consequently, there is a need to repeat the essentials of their experiment using a between subjects design so that carry over effects can not account for the results. The following experiment is intended, in part, to address this need.

A New Experiment

The present experiment replicates the 12 conditions of the Chernikoff and Lemay (1963) study but corrects a number of deficiencies. First, velocity and acceleration control dynamics were used instead of position and acceleration in order to improve the relevance of the data to the types of control dynamics typically found in aviation. Second, the inputs to each axis were the sums of five sinusoids whose phases were randomly set at the beginning of each trial in order to make the signals appear random. Third, a completely randomized between-subjects design was used to eliminate the concern over carry-over effects. Fourth, single axis tracking data were collected from all subjects to serve as a baseline for the dual axis measures. Finally, measures of tracking error were augmented with several other measures in order to clarify the contributions of resource demand and confusions to overall performance. These included measures of control velocity, of subjects' open loop describing functions, of both primary and secondary cross-coherence, and of whether subjects adopted serial or parallel response strategies.

Results of the experiment were expected to clarify the contributions of resource demand, confusions, and compatibility to tracking error. Demand theory and confusions theory lead to incompatible predictions about the effect of the heterogeneity of dynamics on tracking error; therefore, results of the heterogeneity manipulation should show clearly whether resource demand or confusions is the dominant underlying process. Similarly, contradictory predictions about tracking error are made with respect to the manipulation of display integrality so that a clear distinction between confusion and demand processes should again be possible.

With respect to control integrality as well as the compatibility of proximity, confusions and resource processes can not be distinguished on the basis of tracking error alone. In order to distinguish between them, the logic employed was that tracking error not accounted for by documented confusions should be attributed to resource demand. It was expected that control integrality would mainly influence the prevalence of confusions. Further, incompatible display-control configurations and incompatible proximity of displays and dual axis tracking dynamics were also expected to lead to confusions. Demand was expected to be greater under incompatibility only if subjects made the effort to filter out confusions.

METHOD

Subjects

All 96 subjects (88 males and 8 females) were right-handed members of the University of Illinois community who responded to advertisements in the local community. Most were students majoring in engineering. Each subject was tested for tracking ability as described below. Subjects who failed to achieve a satisfactory level of performance on the test were excluded from participation in the experiment. Consequently, all 96 subjects in the final sample possessed a minimum level of tracking ability.

Each subject was paid $3.50 per hour for three hours plus an hourly bonus. For most subjects, the hourly bonus amounted to 50 cents.

Task and Stimuli

The dual axis tracking task was constructed out of two, completely independent single axis compensatory tracking tasks. One tracking task took place in the vertical dimension and one in the horizontal. Thus, the dual axis tracking display consisted of a two-dimensional plane. Whether each axis had its own error cursor or the two shared a common, integrated cursor was one of the experimental variables.

Disturbance inputs. Both disturbance functions were the sum of five digitally created sinusoids. Each function was consistently assigned to the horizontal or vertical axes across subjects and conditions. For the horizontal axis, the five input frequencies were .1304, .2222, .3750, .6383, and 1.1111 hz. For the vertical axis, the five input frequencies were .1705, .2885, .4918, .8333, and 1.4286 hz.

Care was taken to ensure that, among these ten frequencies, none was an harmonic of another. Further, the logarithmic distance between frequencies was maximized within the range of .1304 to 1.4286 hz since the set of ten frequencies were evenly spaced on the logarithmic scale. Spectral analysis recovered the five frequencies for both inputs and showed no evidence of "smearing" or of unwanted spikes at non-input frequencies. The recovered frequencies are displayed in Figure 2.

For both axes, the first three sinusoids with the slowest frequencies had gains of 1.0 while the two high-frequency sinusoids had gains of 0.2. As a result, the contribution of the two highest frequencies to the overall disturbance function was less than that of the three lowest frequencies.

Each disturbance function was calculated prior to the start of each trial. In order to prevent the function from becoming predictable, the phase (i.e., starting point) of each sinusoid was varied randomly from one trial to another. Since the selection of phases for the ten sinusoids were independent of each other, the result was a completely new pair of disturbance signals for every trial.

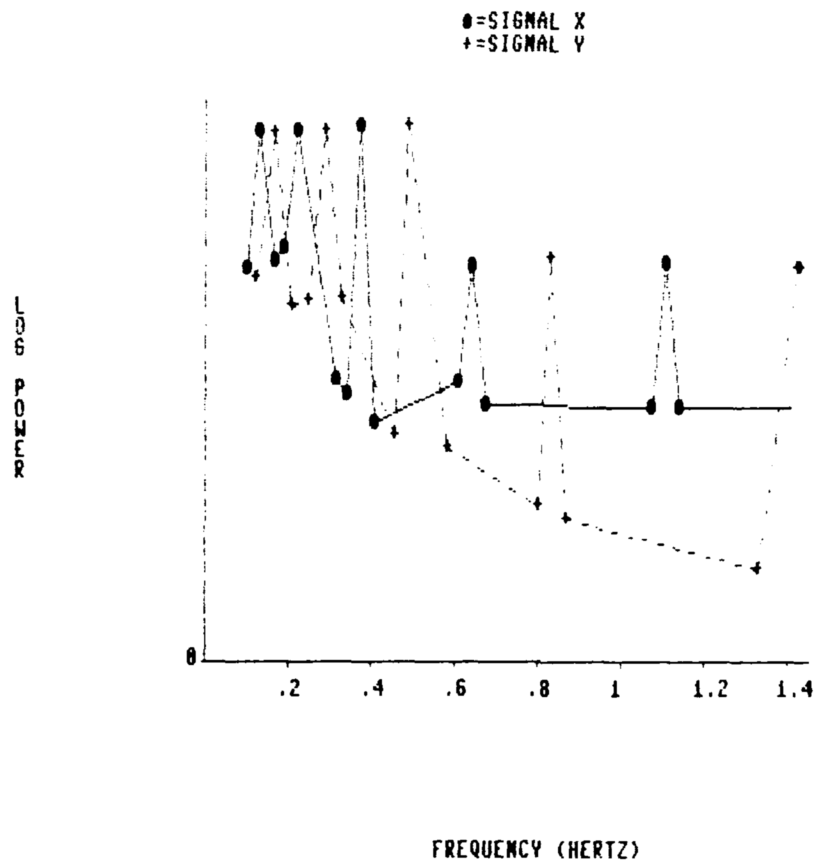

Figure 2. X and Y axis input signals as recovered by spectral analysis. Each signal was the sum of 5 sinusoids. As shown, the frequencies represented in signal X were located in between frequencies represented in signal Y. Note also that the power in the two upper frequencies of each signal was about one-fifth that of the three lower frequencies (the ordinate of the plot is in log scale units).

<u>System dynamics</u>. Two different system control dynamics of pure orders were used: velocity control (first order) and acceleration control (second order). To achieve velocity control, the output signal from the subject's control stick was integrated once before being added to the disturbance signal. To achieve acceleration control, the output signal was integrated twice and then added to the disturbance signal.

<u>Control sticks</u>. Subjects attempted to null vertical and horizontal errors using either separate joysticks for each axis or a single, integrated joystick for both. In either case, vertical movement of the joystick controlled the vertical error cursor ("forward" moved the cursor "up") and horizontal movement controlled the horizontal error cursor. In those conditions in which separate joysticks were used for each axis, which stick controlled the vertical axis and which controlled the horizontal axis was balanced across subjects.

<u>Compensatory tracking display</u>. The same 190 by 190 pixel (13.4 by 13.4 cm) two-dimensional tracking display was used for both dual and single axis tasks (see figure 1). The display was outlined with a yellow box with the zero-error reference indicator placed in the exact center of the box. A small red cross (.5 by .5 cm) in the center of the display served as the reference from which all errors were measured. In the dual axis task, the integrated error cursor consisted of a larger green "plus sign" (.9 by .9 cm) that moved in

both dimensions simultaneously.

The separated cursors consisted of the vertical and horizontal bars of the plus sign. Each bar moved along its own axis only: the vertical bar moved along the horizontal axis and the horizontal bar moved along the vertical axis. For the single axis task, only the relevant error cursor was displayed.

Design

A completely randomized between-subjects design was used in order to avoid transfer effects across conditions. The design consisted of twelve dual axis conditions formed by the factorial combination of three variables: display integrality, control integrality, and heterogeneity of control dynamics.

The display and control integrality manipulations were described in the preceding paragraphs. Manipulation of heterogeneity of control dynamics led to three conditions: velocity control on both axes, acceleration control on both axes, and acceleration control on one axis and velocity control on the other. Which axis received which control order was balanced within each relevant condition.

Procedure

Subjects reported to the laboratory for three experimental sessions. The first session served to introduce subjects to the experiment and to screen out those individuals who were unable to perform the dual axis tracking task. Session two was a practice session and was identical to session three except that data were not recorded. Session three was the focus of the experiment. All reported data were collected in this session. In addition, the calculation of subject's payment bonuses was based on their performance in the third session.

Session one: Subject screening. All subjects performed eight single axis trials and six dual axis trials in session one. All eight single axis trials (4 vertical and 4 horizontal) were performed with acceleration control. Likewise, the first four dual axis trials were performed with acceleration control on both axes. In all instances, display and control integrality conditions were identical to those which the subject would experience in sessions two and three.

At the end of the fourth dual axis trial, a decision was made to either retain the subject in the experiment or to terminate the subject's participation. The decision was based solely on whether the subject had been able to retain control over vertical and horizontal axis errors in any of the dual axis trials. To facilitate this decision, a criterion of an average radial error of 1.0 was adopted where the largest radial error possible was 1.414. Radial error is the square root of the sum of the squared vertical and horizontal errors.

The purpose of this screening procedure was to ensure that subjects admitted into the velocity control conditions were roughly comparable in tracking ability to those in the more difficult acceleration control conditions. Since acceleration control subjects had to be able to maintain control over tracking errors in order to generate meaningful time histories, acceleration control was thought to provide a more appropriate screening task than does the more commonly used critical tracking task (e.g., Miller et al., 1982).

Subjects who failed to meet the radial error criterion were thanked for their participation, given a kind smile, and paid. Subjects who met the criterion then performed two additional trials under the system dynamics they would experience in the rest of the experiment. These subjects were not paid until after the third session. Further, since their bonus was to be based on third session performance (a fact not revealed to the subjects), they were not told the status of their bonus.

Subjects were encouraged to minimize tracking error in two ways. In addition to the possibility of earning bonuses for small tracking errors, subjects were always informed of the lowest errors anyone had achieved in the experiment so far with the same tracking dynamics. (Records were not reported for individual display-control configurations as this could have resulted in different perceived standards among the 12 conditions.) In the dual axis task, the records reported were for radial error. Several subjects indicated that these record low errors were highly motivating.

Sessions two and three. As indicated, sessions two and three were procedurally identical. Subjects first performed a single axis trial, then two dual axis trials, followed by another single axis trial and then two more dual axis trials, and so on for a total of 12 trials. Whether a single vertical or horizontal axis task came first was balanced within each condition.

Throughout each session, the subject sat in a sound and light attenuated booth wearing a set of headphones. All communication between subject and experimenter were via the headphones and a microphone located in the booth out of the subject's line of sight.

The experimenter began each trial by announcing the type of trial to be performed (dual, single-vertical, or single-horizontal), and then asking the subject if he/she was ready. The trial began as soon as the subject responded "ready". Each trial lasted 120 sec. At the end of the trial, the experimenter reported to the subject his or her average horizontal, vertical, and radial axis errors for dual axis trials and as appropriate for single axis trials. The subject was then told what the record low error was up to that time for the type of trial just completed; this message was usually given only once during each session, following the first appropriate trial. The next trial began approximately one minute later. No breaks were otherwise permitted between trials.

Data were collected in the third session only.

Data collected. Two types of data were collected. First, summary data were collected for every trial. Summary data consisted of root mean squared observations of tracking error on the vertical, horizontal, and radial axes, and of control stick movement velocity in both axes.

Second, time series data were collected for the third horizontal and third vertical single axis trials, and for the fourth and sixth dual axis trials. These time series data consisted of five observations per second of the value of eight variables in dual axis trials: the input signal for each axis, the magnitude of displayed error for each axis, and the position of each control stick in the horizontal and vertical axes. Of course, only four of these variables were recorded in single axis trials. These data became the basis for a control theory analysis of each subject's performance.

Assignment to Conditions

Subjects were assigned to the 12 experimental conditions at random with the restriction that all conditions would have an equal number of subjects after every twelfth subject. This assignment strategy helped assure that temporal changes in the available pool of subjects would be represented in each condition.

Apparatus

The experiment was under the control of an IBM Personal Computer running at 4.77 Mhz and updating the tracking display 30 times a second. The display itself was generated on a Princeton Graphics HX-12 color monitor. Subjects's hand controls consisted of two Measurement Systems, Inc. Model 542 joysticks interfaced with the computer via TecMar LabMaster 12-bit A/D inputs. These analog joysticks were spring loaded with 360 deg of motion available. Deflections of the joystick were measured with a resolution of 1/1000 of the total movement radius.

RESULTS

Before presenting the results of the experiment, it will be helpful to first define clearly the data that were analyzed. These data were not the time-series observations themselves but certain useful transformations of those observations. Then, certain features of the data analysis approach will be explained in order to enhance the reader's understanding of what was done. Finally, the adequacy of the single axis data as a baseline against which to compare the dual axis measures will be evaluated.

Data Analyzed

Four types of data were analyzed: root mean squared tracking errors, average control stick velocity, control theory parameters (including remnant and dual axis cross-coherence), and response strategy indicators. Root mean square tracking error (rmse) is the square root of the sum of squared tracking errors which were measured every 200 ms. Control stick velocity was measured as the average absolute difference in deflection in the control stick between measures of control stick position; like tracking error, control stick velocity was also a root mean square measure.

Six control theory parameters were derived: phase intercept, effective time delay (i.e., phase slope), gain intercept, gain slope, primary cross-coherence, and secondary cross-coherence. The derivation of these six parameters was as follows.

First, the entire 120 sec time history for a given trial from a given subject was subjected to a Fourier transform. This transform maps the time history data onto the frequency domain and recovers the sinusoids present in each particular signal. Then, two types of cross-spectra were calculated within bandwidths of .0167 hz centered at the five input frequencies: the cross-spectrum between the input signal and control stick movement, and the cross-spectrum between the input signal and the displayed error. For convenience, these cross-spectra will be said to be collected at the bandwidth's center frequency, the input sinusoid. Thus, separate cross-spectra were obtained for each of the five sinusoids in the input signal. The subject's empirical open loop transfer function (see Wickens, 1986) was determined by dividing the stick cross-spectrum by the error cross-spectrum for each sinusoid. (Complete mathematical descriptions of subjects' transfer functions were not obtained.)

Since cross-spectra are represented as complex numbers, the ratio of two cross-spectra is also a complex number and so may be represented as a vector in the complex plane. This vector is completely described by its length and its angle of rotation from the positive real axis. In control theory terminology, the angle of rotation is referred to as a phase lag since it measures how far the subject lags behind the input sinusoid, and the vector length is referred to as a gain since it measures the ratio of the subject's gain to the signal's gain.

The phase data were calculated in radians. Phase was found to be a linear function of frequency when the input frequencies are also expressed in radians rather than hertz. The slope of the regression of phase on frequency was taken as the subject's internal time delay in which he or she was preparing the next sequence of motor movements (McRuer & Jex, 1967). The intercept of the regression was positive if subjects were anticipating the input signal but negative if they were following the signal.

With respect to the gain data, it was possible to obtain a linear relation between gain and input frequency by taking the logarithm of both. The common logarithm of gain was then multiplied by 20 so that gain was expressed in decibels (dB), and 1.0 was added to the common logarithm of the input frequency (expressed in hertz) to force the gain intercept to be calculated at 0.10 hz. Because the gain function was linear in the current data (a condition which is not true across all frequencies or dynamics), the gain intercept served as an index of the subject's overall gain while the gain slope reflected the degree to which the subject changed his or her gain at higher frequencies. The magnitude and direction of this slope are diagnostic of the subject's response to the system control dynamics: a slope of zero dB per decade (of the common log of the input frequency expressed in hertz) would suggest a zero order (position control) open loop response to a first order system while a slope of 20 dB per decade would suggest a minus first order (differentiating or "lead generating") response to a second order system.

As stated, linear relations between gain and log frequency and between phase and frequency were found. In both the first and second order single axis tasks, the correlations between gain (in dB) and log sinusoid frequency were .92. Similarly, the correlations between phase and sinusoid frequency were .97 for both single axis tasks. In the dual axis tasks, the phase-frequency correlations declined to .90 and the gain-log frequency correlations declined to .80.

Two types of cross-coherence data were also collected. Both types of cross-coherence were computed for bandwidths of .0167 hz centered at the five input sinusoids and then averaged across bandwidths in order to increase their overall reliability (cf., Dunlap, Silver, & Bittner, 1986). The first type of cross-coherence measured was the coherence between the input signal to one axis and control stick movements in the other axis; this type is referred to as primary cross-coherence. A second type, referred to as secondary cross-coherence, is defined only when subjects used two control sticks, one stick for each axis. Secondary cross-coherence is the coherence between an input signal for a given axis and movements of the wrong stick in that axis.

Two dual axis response strategy indicators were derived for each subject. One measured the subject's tendency to alternate control between axes, and the other measured the subject's bias toward one axis or another. Both measures were determined by examining the 600 observations for each subject on the sixth dual axis trial. First, counts were obtained for three types of events: (1) the vertical axis control was off center but the horizontal control was on center (y-alone), (2) the horizontal control was off center but the vertical control was on center (x-alone), and (3) both controls were off center at the same time (both). The x-alone and y-alone counts were then converted to proportions by dividing them by the sum of the three counts (i.e., the total number of observations on which the subject had moved at least one control off center).

Next, the converted x-alone and y-alone measures were represented by a vector in an x,y plane. The origin of the plane may be conceptualized as the point representing a pure parallel control strategy since both controls must always be off center simultaneously if the x-alone and y-alone measures are both zero. Consequently, the length of the obtained vector for any subject represents the "distance" of that subject's response strategy from a pure simultaneous control strategy. Given a vector of length greater than zero, the angle of the vector represents the subject's bias toward one or the other axes. If there were no bias, the angle of the vector would be 45 degrees. Therefore, the bias measure was simply the angle of the vector in degrees minus 45. Thus, a positive bias measure means subjects controlled in the y-axis more than in the x-axis.

A possible objection to the response strategy measures just described is that they do not take into account the fact that the x-and y-axis controls will normally pass through the origin of the control plane at different times even when subjects are engaging in a pure parallel response strategy. One might argue then that the strategy vector might be artificially lengthened as a result. This difficulty can probably be discounted, however, because the position of either control is measured on an essentially continuous scale (having 2000 possible values from -1000 to 1000). As a result, the probability that a continually moving control will be exactly centered at the time its position is measured is virtually zero.

Other ways of determining whether subjects controlled both axes serially or in parallel are, of course, possible. For example, control velocity could have been measured instead of control position. Then parallel responses could have been defined as non-zero velocities on both axes simultaneously. Such a procedure would have been more complicated and would seem to be unnecessary. Because control position always translated into changes in error velocity or acceleration, subjects were unlikely to neglect an axis by holding the control stick off center but at some constant position. Such an event in a given axis could cause the error to change at a constant velocity or acceleration, thus causing the subject to lose control of the error in that axis. (Momentary holds might occur during the course of a "bang-bang" response to a second order system, but they would not indicate neglect.) Thus, using control position as the criterion for determining response strategy seems to be reasonable given the control dynamics under study.

Another possibility would be to have established some small range of movement in control stick position that was considered essentially zero for purposes of this analysis. This approach would allow for noise in the signal from the control stick and so might increase the sensitivity of the analysis. The control sticks used in this experiment were of a very high quality, however, and were virtually noiseless (as determined by running several trials and measuring control stick position without a subject in the subject booth). Further, subjects varied widely in how much they deflected the control stick, and it was feared that defining any small range of movement as essentially zero would lead to false "detections" of no movement for those subjects who generally employed small deflections. Thus, using the criterion of absolutely zero stick deflection seemed to be both a reasonable and a conservative approach to measuring subjects' response strategies.

Finally, it should be noted that the x- and y-axes were treated somewhat differently for subjects in the dynamic heterogeneity conditions. For subjects in the two homogeneous conditions, the x- and y-axes represent the horizontal and vertical control axes, respectively, as would normally be the case. But for subjects in the heterogeneous condition, this mapping is inappropriate since half the subjects had first order dynamics and half had second order dynamics on the horizontal axis. Therefore, the x- and y-axes were arbitrarily redefined so that the first order axis was labeled as x, and the second order axis was labeled as y. As a result, the strategy bias parameter represents bias towards a control order for subjects in the heterogeneity conditions.

Analytic Approach

Prior to analyzing the various measures discussed above, two important decisions were made. First, it was decided to compare the various measures (except the strategy measures) within the first and second order axes separately. That is, instead of including the first and second order homogeneous dynamics conditions in the same analysis, they were each included in separate analyses. In one analysis, then, first order tracking when both axes were first order was compared to first order tracking when the other task was second order. An identical analysis was then conducted for second order tracking.

Although this approach suffers from an inability to test differences between the two homogeneous dynamics conditions, it holds down the total number of tests conducted in the statistical analysis. By resulting in fewer tests, this approach alleviates some of the concern with an escalating experiment-wise type 1 error rate. To the extent that the experiment-wise error rate could therefore be ignored and type 1 error probabilities left uncorrected, the result is that those tests that were conducted are more powerful. Although differences between the two homogeneous control order conditions may be important, they were not the focus of this study. Thus, the loss of the ability to make such comparisons statistically was considered worth the potential gain in power for those comparisons that were of greatest interest.

Second, it was decided to average measures (again, except for the strategy measures) across the vertical and horizontal axes in the two homogeneous control order conditions. While differences between the two axes would be important in experiments concerned with axis independence in general, they were not of interest in the present experiment. Similarly, control hand was not analyzed since this variable was not of interest in this study, and its inclusion would have detracted from the power of the rest of the analysis.

As a result, all variables--except the strategy measures--were analyzed in two 2 X 2 X 2 (display integrality by control integrality by dynamic heterogeneity) analyses of variance (ANOVA), one for each control order. The strategy variables were analyzed in a 2 X 2 X 3 ANOVA since analysis of the control orders separately would have defeated the purpose of the analysis.

Since the global analyses of the various dependent variables were planned in advance of the experiment, no attempt was made to gaurd against an escalating experiment-wise type 1 error rate. Further, all of the contrasts reported within a given variable were planned and orthogonal; thus, no attempt was made to control family-wise type 1 error rates (see chapter 8 in Keppel (1982) for a discussion of this approach). There was one exception to this last statement (in the strategy bias data, which were exploratory); in that case, Tukey's method for correcting the family-wise error rate was used.

Single Axis Task Baselines and Dual Axis Decrements

Ideally, single axis task performance should not have been affected by the experimental manipulations and therefore should have remained constant across groups. Thus, it should provide a baseline against which to compare the effects of the experimental conditions on all of the dual axis measures except the strategy and cross-coherence measures. Consequently, instead of analyzing the dual axis measures directly, one could profitably analyze the difference between those measures and their single axis counterparts. Such differences will be referred to as dual axis decrements. These decrements were calculated individually for each subject by subtracting that subject's single axis measure on a particular dependent variable from his or her dual axis measure.

Two theoretically important issues are associated with dual axis decrements, as with dual task decrements in general. First, although decrements are empirically meaningful in and of themselves, theoretical inferences drawn from these decrements depend upon vertical axis tracking (for example) being fundamentally the same under dual axis conditions as under single axis conditions. To the extent that such equivalence is violated, decrements may be difficult to interpret. A second difficulty with decrements is that their variance is comprised of two components: one component is unique to the dual axis task and one is unique to the single axis task. The component of variance common to dual and single axis tracking is removed when the decrement is computed. While the act of computing decrements implies that one wishes to analyze the variance component unique to the dual axis task, it is not clear that one also wishes to analyze the component unique to the single axis tasks.

In response to the equivalence issue, task equivalence under single and dual axis conditions is usually assumed. The reason for such assumption is that equivalence is virtually impossible to prove yet is often needed in order to make any sort of theoretical inferences possible. The second difficulty is often dealt with by subtracting the sample single axis mean from each subjects' dual axis score. This procedure avoids the problem of adding a single axis variance component to the decrement variance because the sample mean is a constant within the sample. But for the same reason, subtracting the sample mean leaves the dual axis data essentially unchanged except that the dual axis grand mean is lowered. Thus, subtracting the sample single axis mean is equivalent to doing nothing to the dual axis data. Consequently, subtracting each subject's single axis score from his or her dual axis score seems to be the most useful way of deriving dual axis decrements in spite of the difficulty with respect to the unique single axis variance component.

Before computing dual axis decrements, an effort was made to determine whether single axis performance was insensitive to the dual axis experimental manipulations. While the assumption of single axis insensitivity to the experimental manipulations held up for most of the measures, it failed for both of the gain measures, intercept and slope (see Damos & Lintern, 1981, for a similar sensitivity of single axis gain). Both variables were influenced by the heterogeneity of dynamics manipulation ($p < .05$) in the same direction as in the dual axis tasks.

Because the sensitivity of single axis gain to the heterogeneity of dynamics manipulation is most readily interpreted as a carry over effect from the dual axis task (cf., Damos & Lintern, 1981), it seemed prudent not to rely on dual axis decrements in the gain measures. Consequently, both dual axis gain intercept and gain slope were analyzed directly in place of the decrements. Decrements were analyzed for all other variables where they were defined.

Error and Control Velocity Dual Axis Decrements

Most psychological studies of tracking behavior use error as the dependent variable; thus, the dual axis error decrements provide the major link between the present and previous studies. As is typically found, all error decrements were positive, indicating that dual axis error was greater than single axis error.

Evaluation of trials effect. Before presenting the dual axis error decrements, it is important to evaluate the potential loss of information about the effect of practice since the decrement measures necessarily collapse data across trials. Figures 3 and 4 display the mean dual axis errors by trial (session 3 only) for the first and second order axes, respectively. Each figure displays the practice effect for the heterogeneous and homogeneous dynamics conditions separately.

To determine whether the practice effect varied systematically with the eight experimental conditions, an analysis was carried out on the linear, quadratic, and cubic components of the trials effect. The statistical approach taken was to perform a complete 2 X 2 X 2 ANOVA on each of the three components and then to adjust the resulting p-values by a Bonferonni correction. This approach avoids the difficulties of the univariate mixed model approach to within-subjects measures and passes over the multivariate step in the MANOVA approach to such measures (cf., Harris, 1985; O'Brien & Kaiser, 1985). (Higher order contrasts were not analyzed due to their uninterpretability.)

The above analysis of the error data by trials detected only one marginally reliable effect of the experimental manipulations: the quadratic component of the homogenous first order axis was larger than that of the heterogeneous first order axis as is evident in Figure 3, $F(1,56) = 5.87$, $MS_e = 13965.13$, Bonferonni $p = .0549$. Since no other reliable effects were detected in either the first or

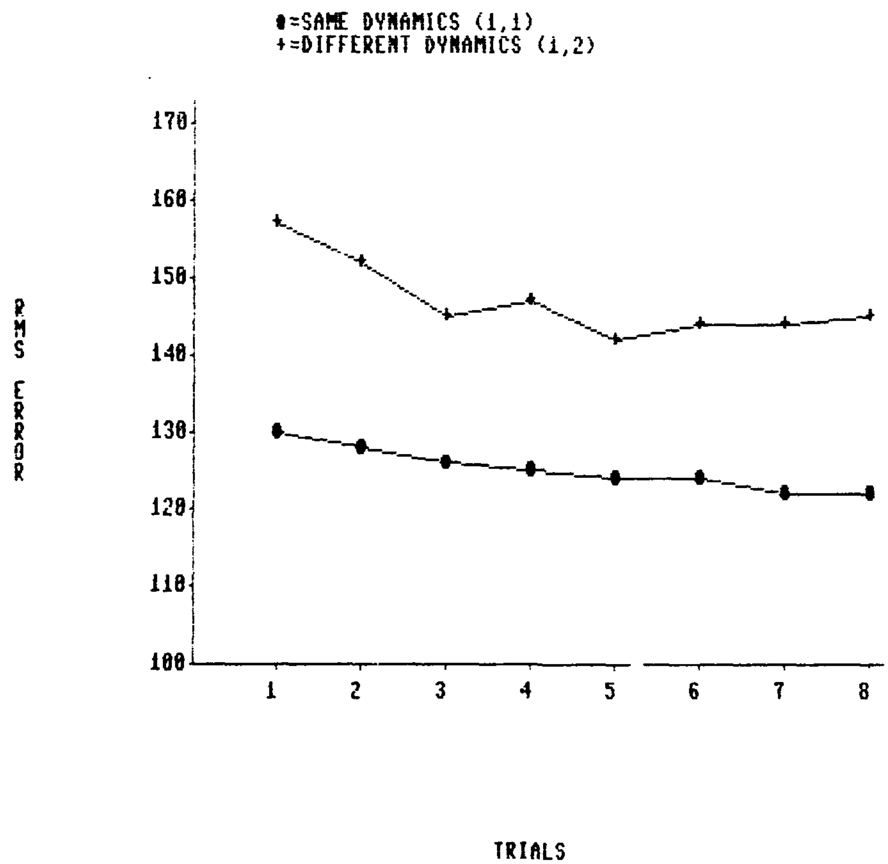

Figure 3. First order rms error over dual axis trials in session 3. This figure and the next show the effect of practice as a function of whether dynamics on the two axes were the same or different.

NOTE: In these and the following figures, the numbers shown in parenthesis in the form (a,b) refer to control dynamics: a refers to the dynamics on the axis represented in the figure, b refers to the dynamics on the paired axis (not represented in the figure). In all cases, data are averaged across vertical and horizontal axes.

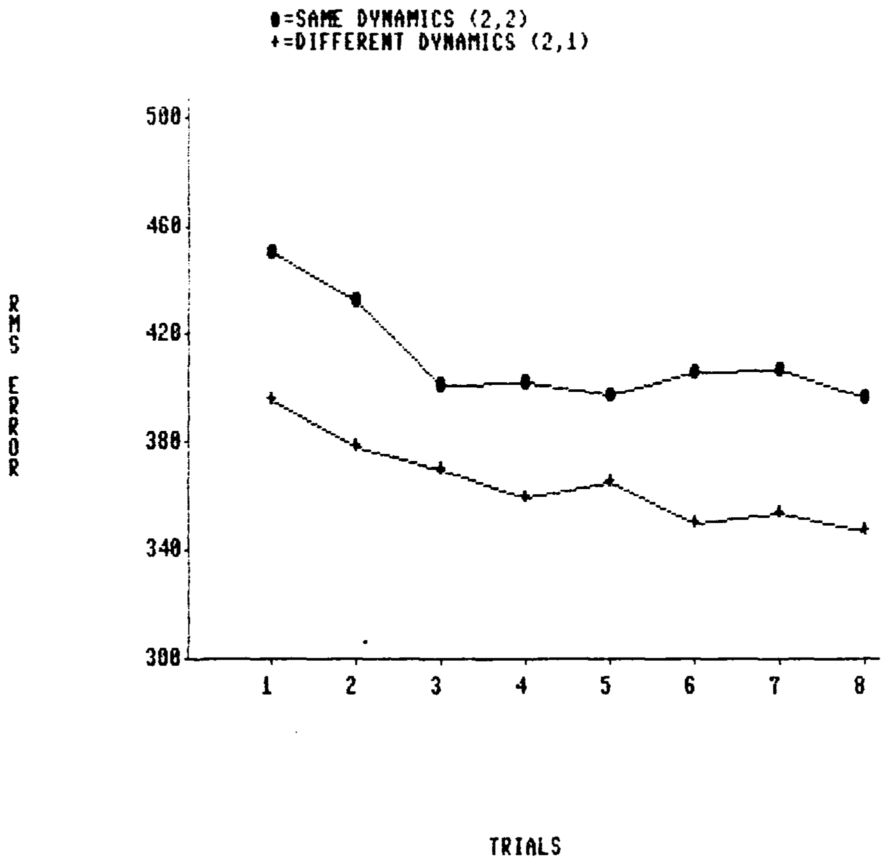

Figure 4. Second order rms error over dual axis trials in session 3. Again, the effect of practice is shown as a function of whether dynamics on the two axes were the same or different.

second order axes, it is concluded that collapsing the error data across trials entailed only a minimal loss of information with regard to the experimental manipulations.

Error decrements. Figures 5 and 6 display the dual axis decrements in root mean square error in each of the eight experimental conditions for first and second order tracking, respectively. In Figure 5, an effect of heterogeneity of dynamics is evident in which the first order tracking error decrement is less when both axes are first-order than when one is second order, $F(1,56) = 9.48$, $MS_e = 306.11$, $p = .0032$. An heterogeneity effect is also evident in Figure 6, but here the error decrement is less in the heterogeneous condition--that is, second order tracking is disrupted more by having second rather than first order dynamics on the other axis, $F(1,56) = 19.02$, $MS_e = 3136.52$, $p < .0001$.

An interaction of display type (integrated or separated) with heterogeneity of dynamics also appears in both figures: $F(1,56) = 7.14$, $MS_e = 306.11$, $p = .0099$ (first order axis); $F(1,56) = 5.91$, $MS_e = 3136.52$, $p = .0183$, (second order axis). In both figures, the error decrement was increased by separated displays when the dynamics were the same on both axes (first order $F(1,56) = 5.72$, $p < .05$; second order $F(1,56) = 14.60$, $p < .001$) but not when the dynamics were different (first order $F(1,56) = 1.91$, $p > .10$; second order $F(1,56) = 0.15$, $p > .25$). Although a display type by control type interaction also seems evident in Figure 6, it was not reliable,

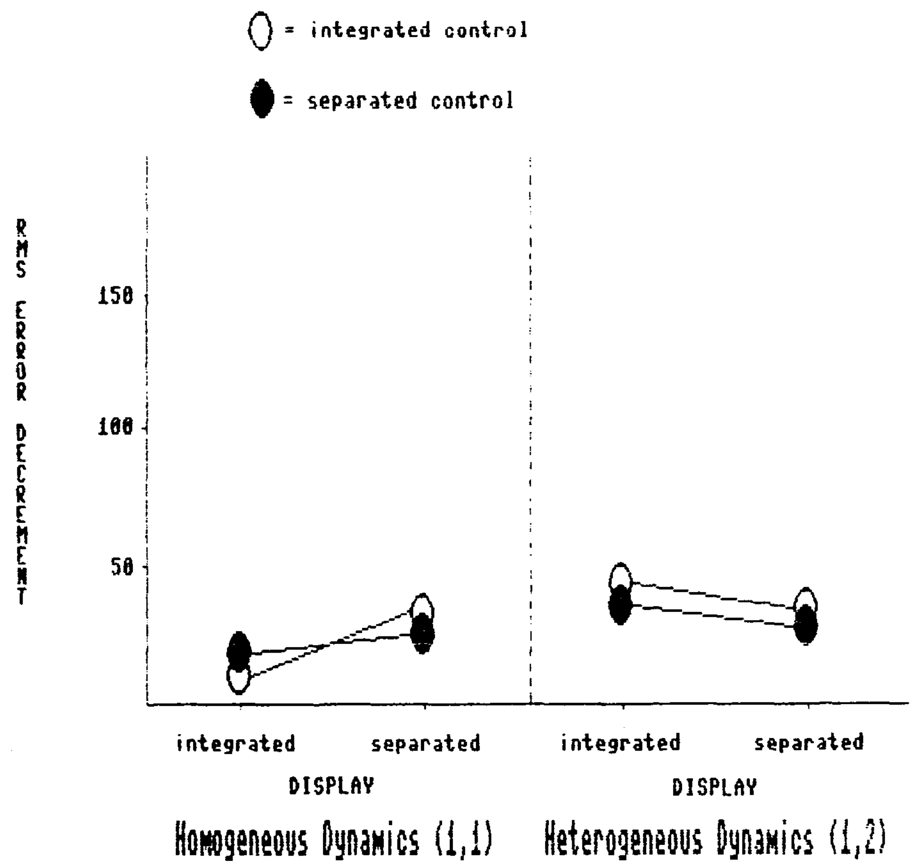

Figure 5. First order dual axis error decrement as a function of the eight experimental conditions. All dual axis decrements reported in this study were calculated individually for each subject. In the present case, each subject's single axis error was subtracted from his or her dual axis error.

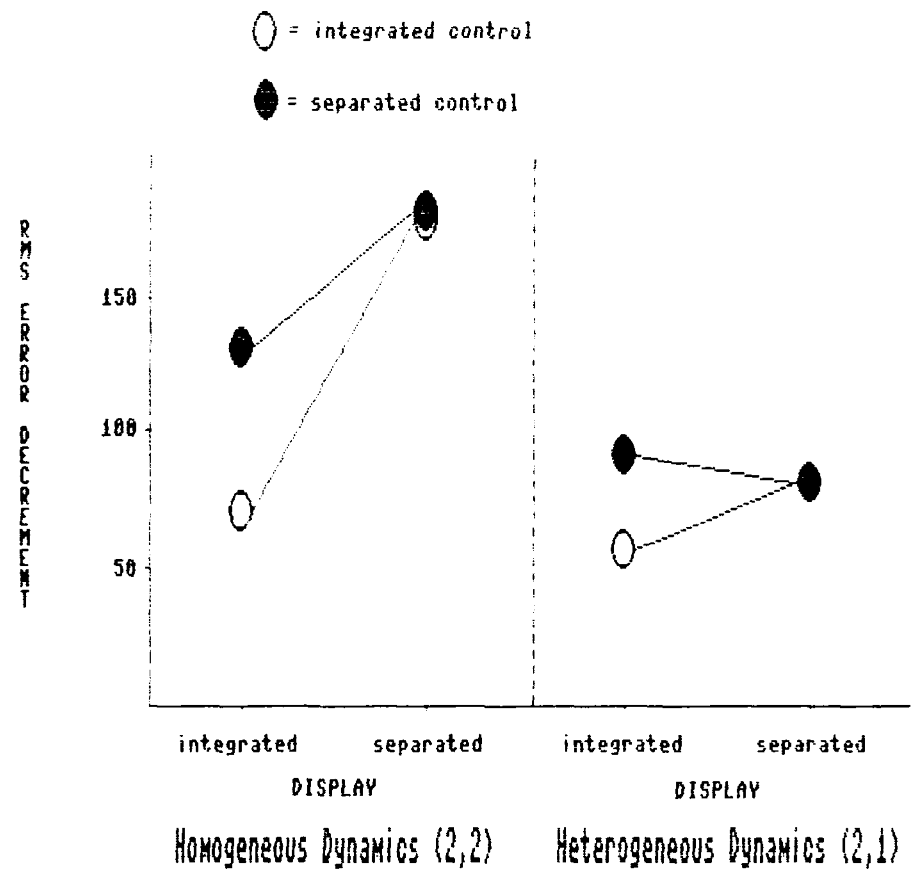

Figure 6. Second order dual axis error decrement as a function of the eight experimental conditions.

$F(1,56) = 2.65$, $MS_e = 3136.52$, $p = .1089$.

Control velocity decrements. While error decrements index the deterioration of subjects' performance in the dual axis task, control stick velocity decrements index both the change in the frequency and average size of control stick movements. As such, they indicate whether subjects have grown more or less cautious in attempting to control error, assuming that control effort is unchanged. Positive decrements (i.e., increments) indicate a decrease in caution while negative decrements indicate an increase in caution relative to the single axis task.

Figures 7 and 8 plot the control velocity decrements in each of the eight conditions for the first and second order axes, respectively. The figures are arranged so that small decrements are plotted above large decrements.

Note that in first order tracking (Figure 7), the velocity decrements tend to be near zero under homogenous control orders and negative under heterogeneous control orders. For second order tracking (Figure 8), the opposite pattern appears: the decrements tend to be negative under homogeneous dynamics and positive under heterogeneous dynamics. In both cases, the effect of heterogeneity of dynamics was reliable: $F(1,56) = 10.75$, $MS_e = 4442.71$, $p = .0018$ (first order); $F(1,56) = 8.98$, $MS_e = 21616.73$, $p = .0041$ (second order). Thus, the effect of heterogeneous dynamics seems to be to increase the control velocity of the second order axis and to decrease that of the other axis. Phrased in other terms, having second order dynamics on one axis leads to a reduction in control velocity on the other axis.

Also evident in both figures is a display type by control type interaction. This interaction appears to be a compatibility of integrality effect since the control velocity decrement is less when controls and displays are both integrated or both separated than when one was integrated and the other was integrated. This interaction was reliable in the first order task ($F(1,56) = 5.02$, $MS_e = 4442.71$, $p = .0290$) but not in the second order task ($F(1,56) = 1.63$, $MS_e = 21616.73$, $p = .2070$).

Closer examination of the interaction revealed that when controls were integrated, display integrality had no reliable effect on control velocity, $F(1,56) = 1.25$, $p > .25$; but when controls were separated, then separated rather than integrated displays led to smaller decrements in control velocity, $F(1,56) = 4.20$, $p < .05$.

Control Theory: Human Open Loop Transfer Functions

According to the Cross-Over model of human tracking performance, the human will adjust his or her own open loop transfer function so that the human-control system open loop transfer function is first order. Thus, if the control system is already first order, the human will act like a zero order system with a gain slope of zero dB per decade and a phase intercept of zero degrees. That is, a perceived error position will generate a proportional controlled response

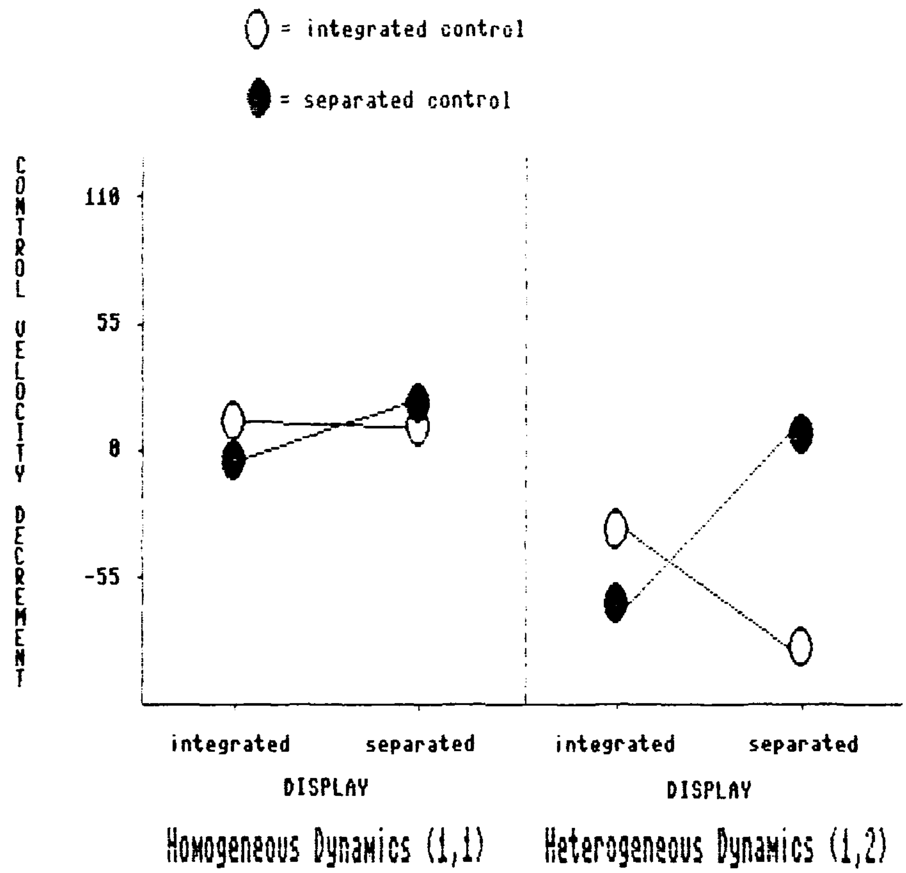

Figure 7. First order dual axis control velocity decrement as a function of the eight experimental conditions. In this and the next figure, points plotted higher in the figure represent smaller decrements.

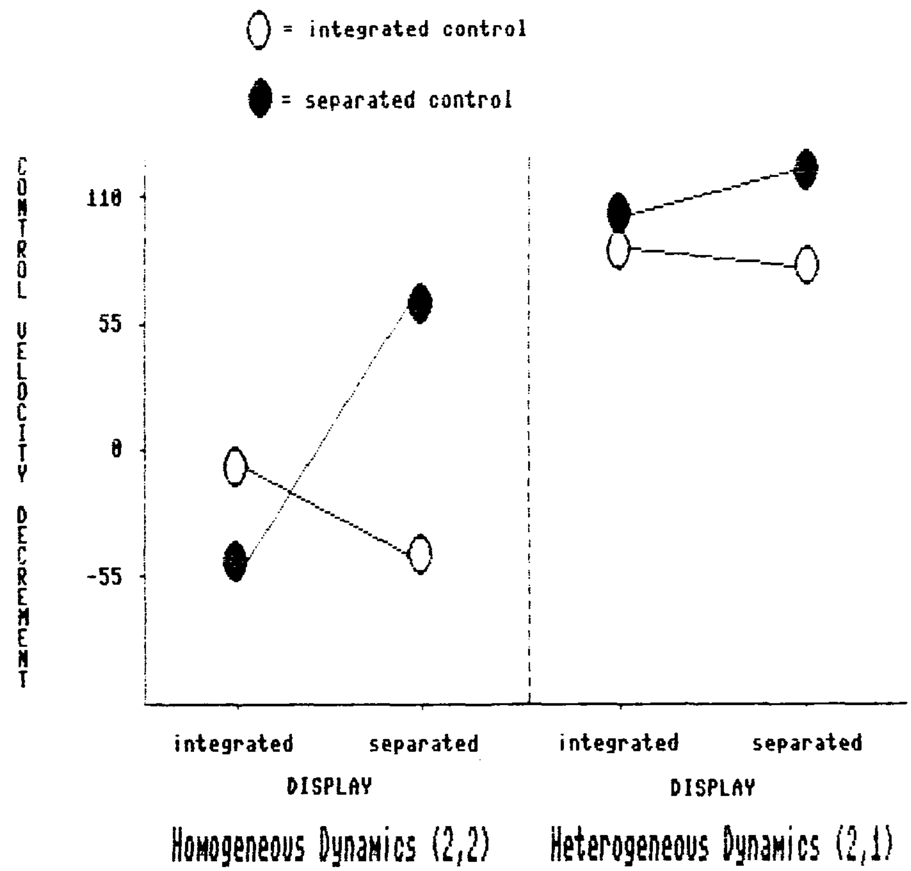

Figure 8. Second order dual axis control velocity decrement as a function of the eight experimental conditions.

position. But if the control system is second order, then the human will act like a minus-first order "lead generating" system with a positive gain slope of 20 dB per decade and a phase intercept of 90 degrees. That is, a perceived error velocity will generate a proportional controlled response position.

Figures 9 and 10 display the average transfer function Bode plots for single and dual axis tasks. (Single axis phase functions were indistinguishable from the dual axis functions and so are not shown.) Table 1 displays the gain intercept, gain slope, phase intercept, and effective time delays for the axes shown in both figures. Figure 9 is for the first order axes and Figure 10 is for the second order axes. Note that the first order gain slopes are all slightly positive (about 6 dB per decade) while the phase intercepts are around -2 degrees. The second order gain slopes are much steeper (about 14 dB per decade) with phase intercepts around 28 degrees. These data indicate that subjects did respond to the first order task by adopting an essentially zero order open loop response. While subjects' response to the second order task was not optimal with respect to the cross-over model (a gain slope of 20 dB per decade with a phase intercept of 90 degrees), it was essentially a minus first order response to a second order system.

The phase plot of both figures shows a lag increasing exponentially at higher values of log frequency. This lag represents the contribution of a constant effective time delay. The effective

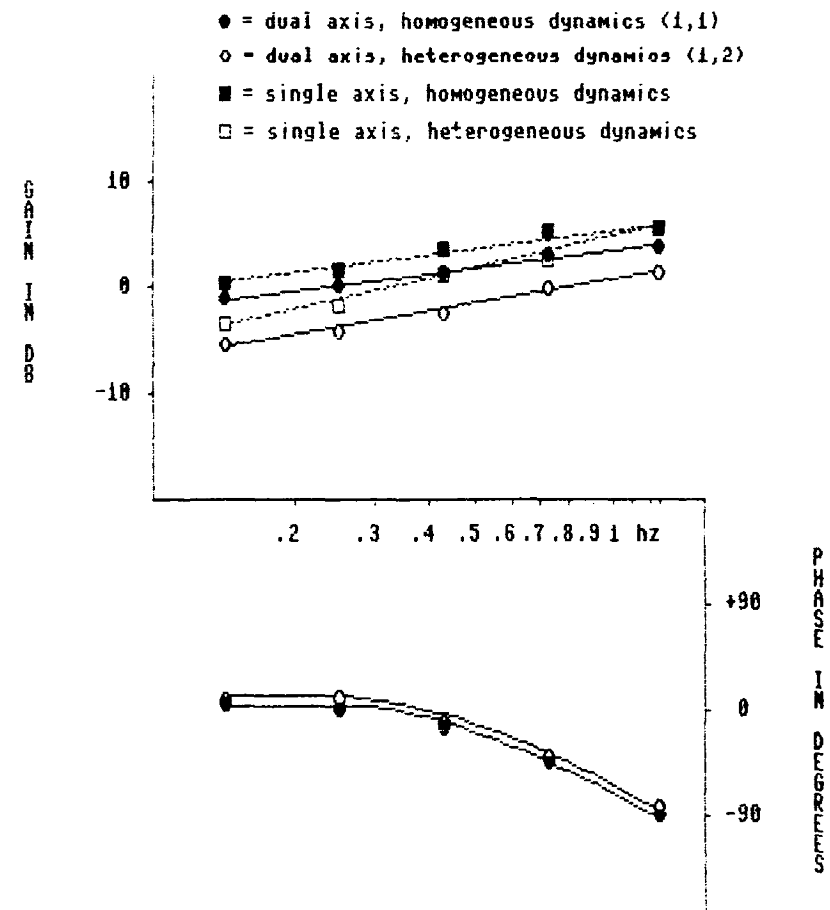

Figure 9. First order axis subject open loop responses for the single and dual axis tracking tasks under homogeneous and heterogeneous control dynamics. Plotted gain and phase points are the observed data averaged across subjects. Least squares estimates of the gain and phase functions are also shown. Single and dual axis phase data are indistinguishable in this figure.

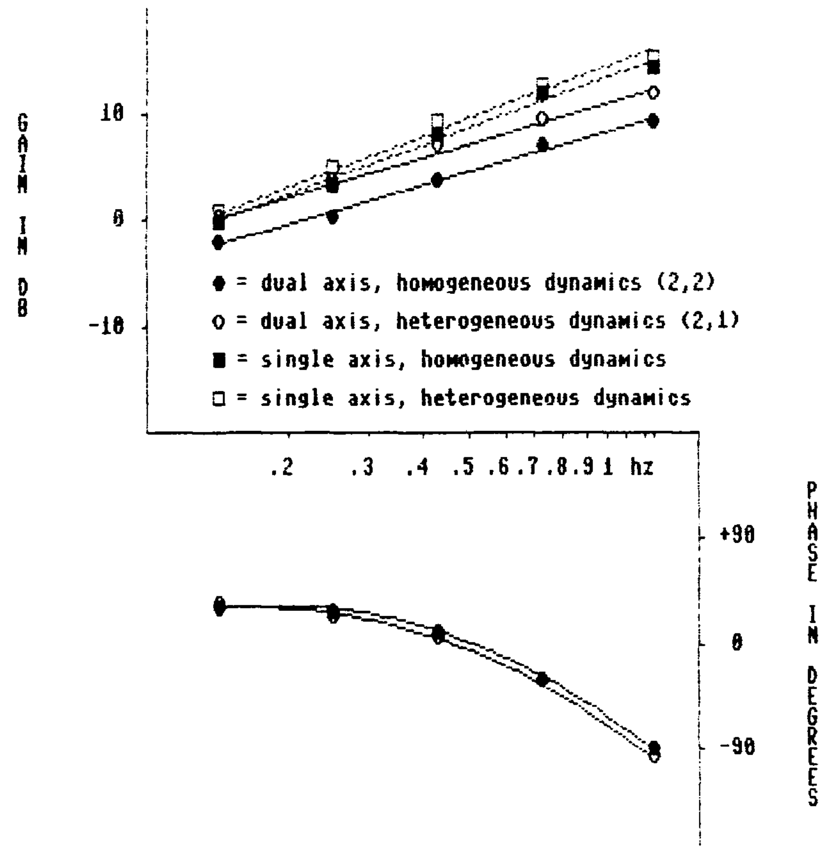

Figure 10. Second order axis subject open loop responses for the single and dual axis tracking tasks under homogeneous and heterogeneous control dynamics. As in the previous figure, single and dual axis phase data are not distinguishable.

Table 1

Dual and Single Axis Human Open Loop Transfer Functions: Gain and Phase Data

	Gain Intercept (dB)	Gain Slope (dB/dec)	Phase Intercept (degrees)	Effective Time Delay (ms)
First Order Axis				
Single axis	-1.13	5.65	-1.97°	232
Dual axis				
Same Dynam	-3.56	5.52	-3.30	245
Diff Dynam	-8.65	7.78	0.80	242
Average	-4.45	6.32	-2.02	240
Second Order Axis				
Single axis	-1.03	15.49	35.53	344
Dual axis				
Same Dynam	-5.85	12.96	23.09	319
Diff Dynam	-3.00	13.04	23.97	340
Average	-3.29	13.83	27.53	334

time delay measures (i.e., phase slope; see "Data Analyzed" for the linearizing transformations used) conform well to those specified by McRuer and Jex (1967) in their review of human open loop transfer functions. When applied to the bandwidths used in the present study of 2.4 and 3.1 radians per sec, their review suggested a first order effective time delay of 175 to 200 ms and a second order time delay of about 320 to 350 ms. The corresponding effective time delays obtained here were about 240 and 334 ms, respectively.

Gain. Figures 11 and 12 display the gain intercepts for first and second order axes in each of the eight experimental conditions. Figures 13 and 14 similarly display the gain slopes. Only the heterogeneity of control dynamics reliably influenced the gain intercepts for either task (Figures 11 and 12). For the first order axis, the gain intercepts were attenuated when the control dynamics were second rather than first order on the other axis, $F(1,56) = 6.98$, $MS_e = 59.52$, $p = .0107$. For the second order axis, the gain intercepts were likewise attenuated when the control dynamics were second rather than first order on the other axis, $F(1,56) = 4.47$, $MS_e = 29.18$, $p = .0390$.

Notice that the effect of dynamics heterogeneity on gain is the same as its effect on control velocity reported above. This correspondence is expected since both measures express, in different domains, the amount of control activity expended to reduce perceived error. In both cases, control activity is diminished when second

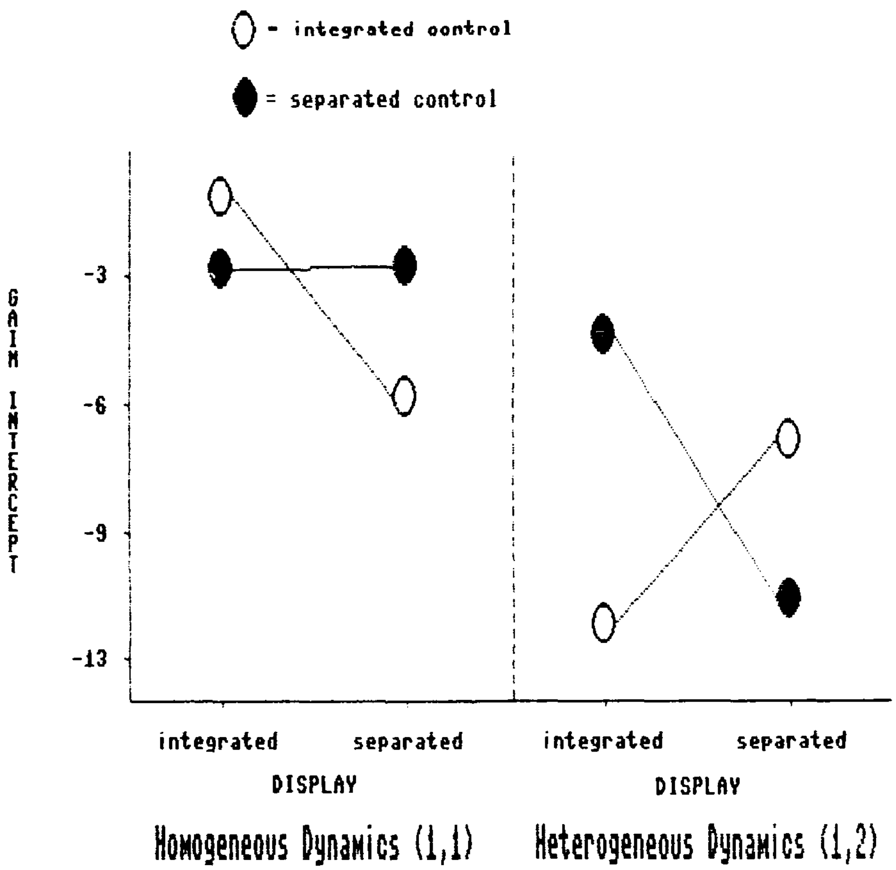

Figure 11. First order dual axis gain intercept of subjects' open loop responses in the eight experimental conditions. Gain is measured in decibels.

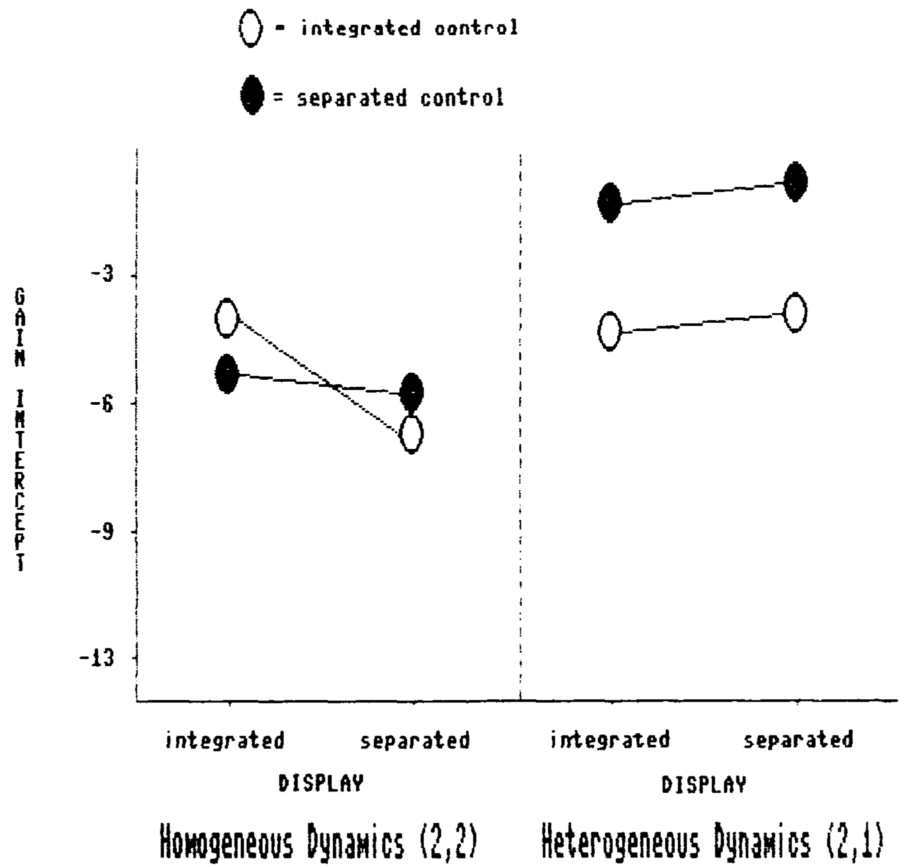

Figure 12. Second order dual axis gain intercept of subjects' open loop responses in the eight experimental conditions. Gain is measured in decibels.

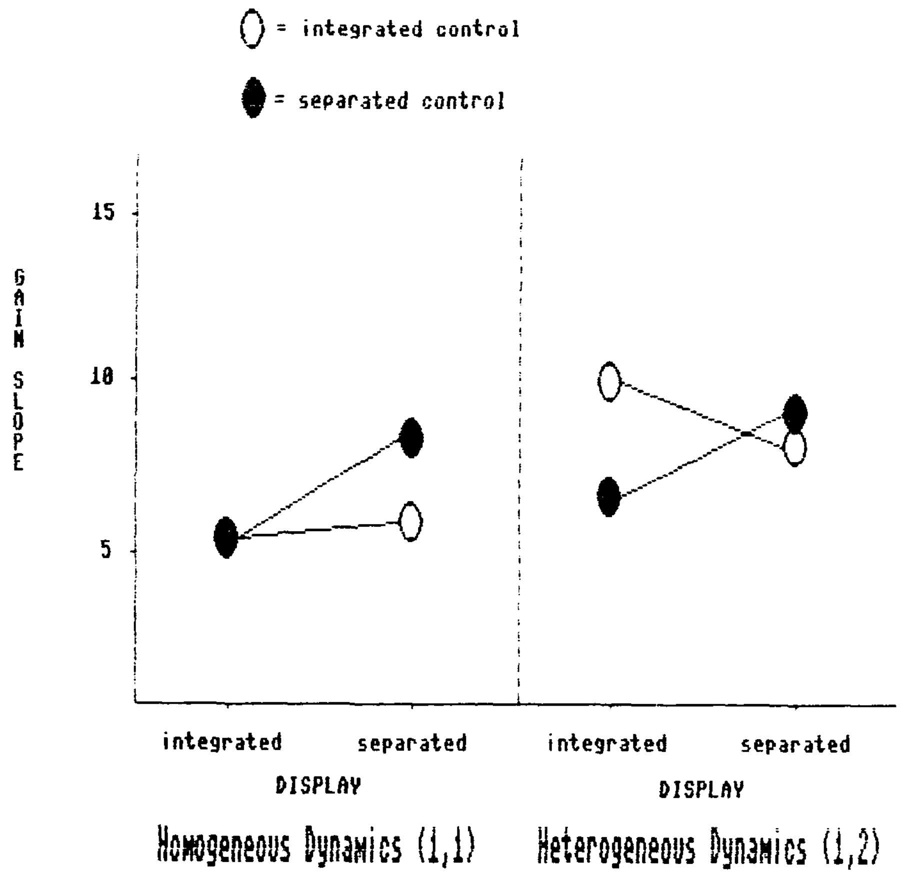

Figure 13. First order dual axis gain slope of subjects' open loop responses in the eight experimental conditions. Slope is expressed in decibels per decade.

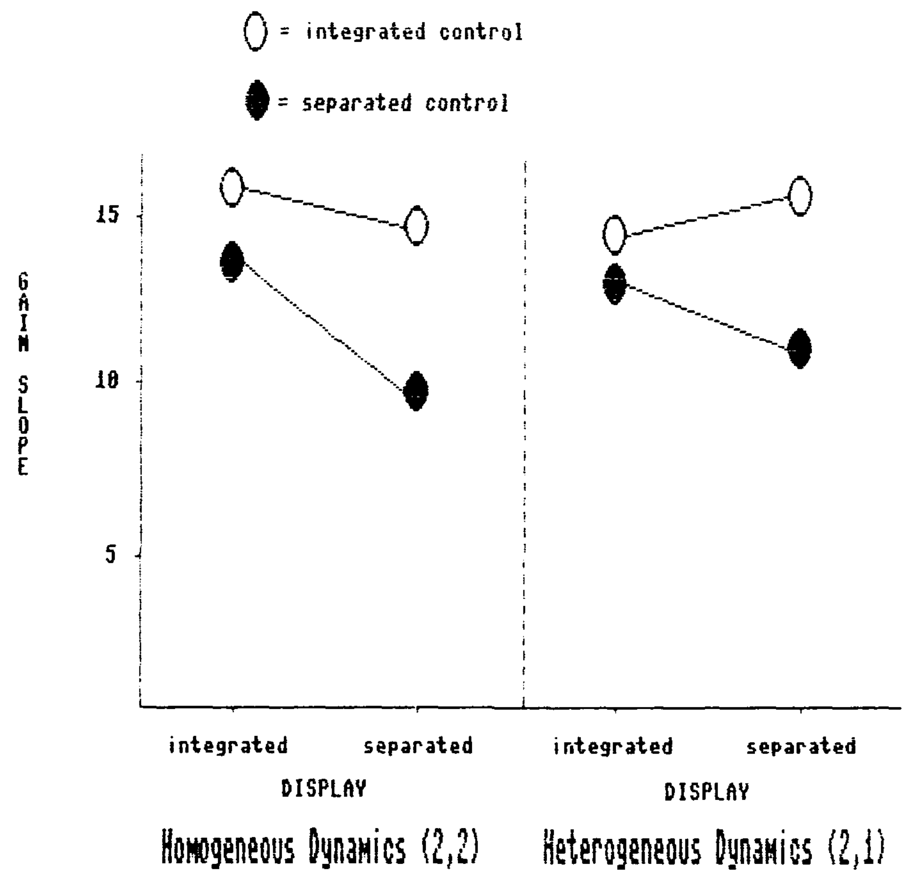

Figure 14. Second order dual axis gain slope of subjects' open loop responses in the eight experimental conditions. Slope is expressed in decibels per decade.

order dynamics are present on the other axis, an effect well replicated in the literature (Wickens, 1986b; Gopher & Wickens, 1977).

Dynamics heterogeneity affected gain slopes in the first order axis ($F(1,56) = 4.11$, $MS_e = 19.85$, $p = .0474$) but not in the second order axis ($F(1,56) = 0.01$, $MS_e = 20.49$, $p > .93$). That is, the presence of second order dynamics on one axis steepened the first order gain slope, but the presence of first order dynamics on one axis had no effect on the second order gain slope.

Although dynamics heterogeneity had no affect on second order gain slope, control type did. Second order gain slope was steeper when an integrated control was used for both axes rather than when separate controls were used, $F(1,56) = 8.94$, $MS_e = 20.49$, $p = .0041$. The same effect was absent in the first order gain slope ($p > .96$).

Phase. Phase intercept was not reliably influenced by any of the dual axis experimental manipulations. The overall first and second order dual axis decrements in phase intercept were reliable, however. The first order phase intercept declined 7 degrees in dual axis tracking, $F(1,63) = 9.24$, $MS_e = 0.002$ (units in radians), $p = .0035$; the second order intercept declined by 12 degrees, $F(1,63) = .04$, $MS_e = 0.002$ (units in radians), $p < .0001$.

As reported above, the presence of second order dynamics on one axis steepened the first order gain slope. One interpretation of this effect is that the second order axis may have induced subjects to needlessly generate a small amount of phase lead in the first order axis. If so, then one would expect the first order phase intercept of subjects tracking with heterogeneous dynamics to be higher than that of subjects tracking with homogeneous dynamics. The first order phase intercept of the heterogeneous dynamics group was in fact 4 degrees higher than those in the homogeneous dynamics group, but the effect was not statistically reliable, $F(1,56) = 1.37$, $MS_e = 0.06$ (units in radians), $p = .2460$.

Unlike phase intercept, effective time delay (phase slope, computed as described earlier) was influenced by the dual axis experimental manipulations under second order tracking. (No reliable effects were observed under first order tracking; $MS_e = 0.009$, units in seconds.) Figure 15 displays the dual axis decrement (i.e., the increase) in effective time delay in the second order axis for each of the eight experimental conditions. The figure is arranged so that small decrements are plotted above large decrements.

These decrements in effective time delay show the display type by control type interaction expected if a mapping operation is required when the integrality of displays and controls do not match. That is, effective time delay was 132 ms shorter when display and control type were both the same (i.e., integrated or separated) than when one was integrated and the other was separated, $F(1,56) = 6.46$, $MS_e = 0.011$ (units in seconds), $p = .0138$. Examination of this interaction showed that control integrality had no reliable effect

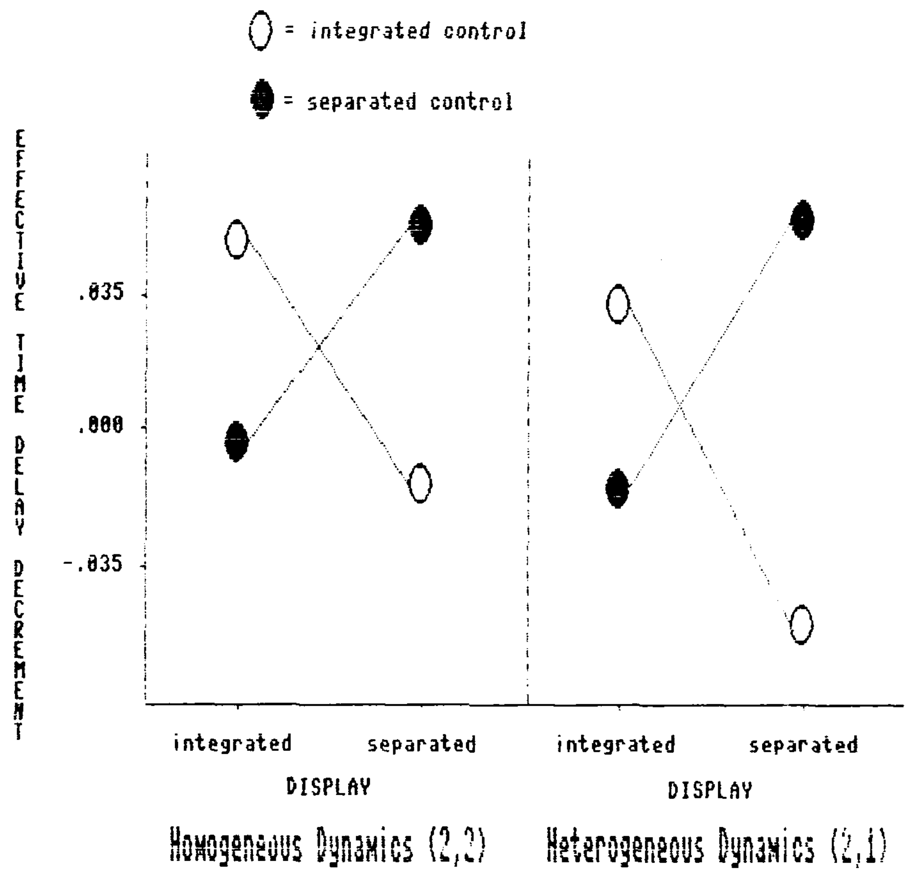

Figure 15. Effective time delay decrement in the second order axis for each of the eight experimental conditions (in seconds). No significant effects appeared in the first order axis. Points plotted higher in the figure represent smaller decrements.

when displays were integrated, $F(1,56) = 1.77$, $p > .10$; but when displays were separated, separated controls led to shorter time delays than did integrated controls, $F(1,56) = 5.14$, $p < .05$.

<u>Cross-Coherence</u>. Primary cross-coherence (coherence between the input signal to one axis and control stick movements in the other axis) is shown in Figures 16 and 17 for the first and second order control axes, respectively. Both figures suggest that primary cross-coherence was greater with integrated rather than separated controls and possibly with integrated rather than separated displays. The control type effect was reliable in both the first and second order axes, $F(1,56) = 4.73$, $MS_e = 0.007$, $p = .0338$, $F(1,56) = 8.20$, $MS_e = 0.004$, $p = .0059$, respectively; the display effect, however, was not strongly reli e for either control order ($p = .0820$, $p = .1106$, respectively). No other effects were statistically reliable in either figure, including the main effect of heterogeneity. That is, the increase in RMS error decrements in the first order axis with second order dynamics on the other axis does not seem attributable to cross-coherence.

Secondary cross-coherence, defined only in the separated controls condition, may be thought of as an index of confusions between control sticks. This type of cross-coherence is displayed in Figure 18 for the first and second order axes. It is evident that secondary cross-coherence was greater given an integrated error display rather than two separate error displays, $F(1,28) = 11.38$,

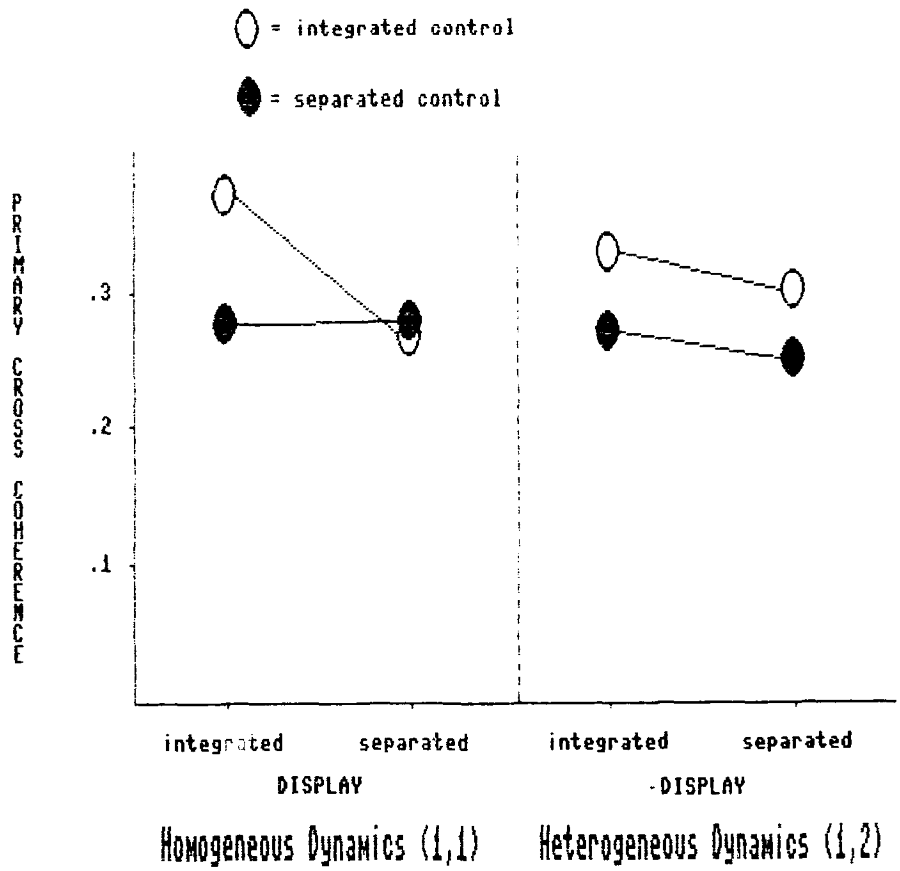

Figure 16. First order primary cross-coherence (i.e., confusions between which signal goes to which axis) in the eight experimental conditions. Cross-coherence is the control theory equivalent of a squared correlation and may be interpreted as such.

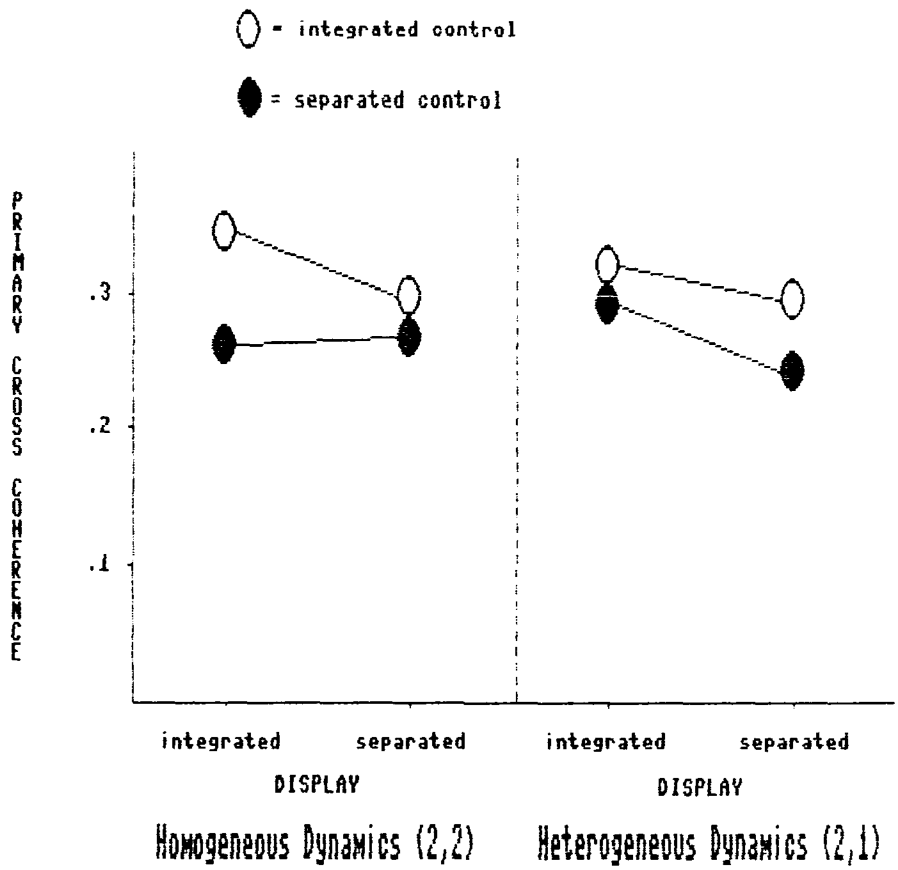

Figure 17. Second order primary cross-coherence in the eight experimental conditions.

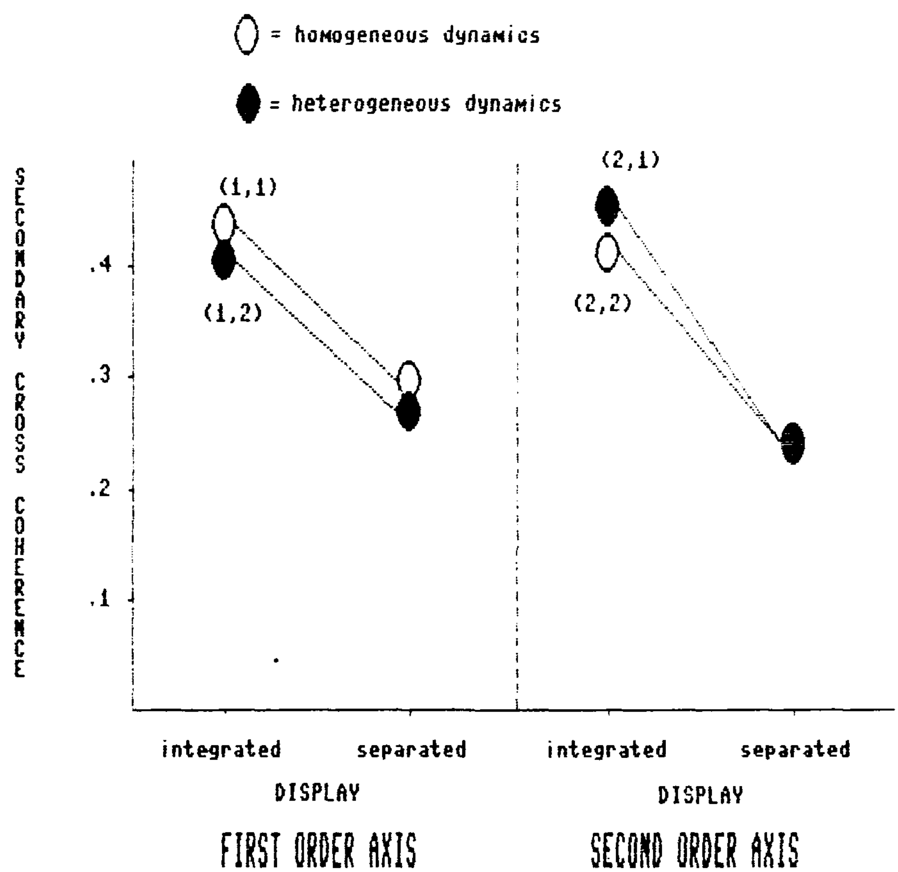

Figure 18. Secondary cross-coherence (i.e., confusions between which stick controls which axis) in each applicable condition. Secondary cross-coherence is defined only when separate control sticks are used for the two axes. Note that confusions between control sticks do not directly affect the error in either axis.

MS_e = 0.0135, p = .0022, F(1,28) = 13.73, MS_e = 0.021, p = .0009, respectively. No effects of dynamics heterogeneity are apparent in the figure and none were detected statistically.

Alternating versus Simultaneous Control Strategies

The strategy measures (i.e., the length and angle of the strategy vector as described earlier) are shown in Figures 19 and 20. Recall that the switching measure may be thought of as the distance of the subject's response strategy away from pure parallel control. (This distance measure is less than, but monotonically related to, the proportion of time subjects spent alternating between axes rather than controlling both simultaneously.) In Figure 19, the response strategy of subjects in the homogeneous control order conditions appears to have been closer to a parallel strategy than that of subjects in the heterogeneous dynamics conditions. Note, however, that all three groups of subjects spent the majority of their time controlling in both axes simultaneously.

The main effect for the heterogeneity manipulation was reliable, $F(2,84) = 2.98$, MS_e = 0.009, p = .0564; and Tukey's test for pairwise comparisons showed that while both first and second order homogeneous subjects differed from heterogeneous subjects ($p < .10$), the homogeneous subjects did not differ from each other. No other reliable effects were found among the switching measures.

As explained earlier, the bias parameter measures the deflection of the strategy vector in degrees from an unbiased 45 degrees. Thus, an unbiased strategy vector would have a deflection of zero degrees, and the maximum deflection possible is plus or minus 45 degrees. As with the switching measures, the heterogeneity effect was reliable, $F(2,84) = 46.29$, $MS_e = 211.89$, $p < .0001$. Subjects in both the first and second order homogeneous dynamics groups were relatively unbiased (positive 3.10 and 3.67 degrees deflections, respectively) while subjects in the heterogeneous dynamics groups were strongly biased toward the second order axis (a positive 33.71 degrees deflection).

Although a possible display by control interaction may exist among the bias measures (especially in the homogeneous groups), it was not reliable ($F(1,84) = 3.04$, $MS_e = 211.89$, $p = .0848$). The main effect for control integrality was statistically significant, however; $F(1,84) = 4.88$, $MS_e = 211.89$, $p = .0299$. The nature of this effect is that subjects were more likely to be biased toward the vertical axis. But recall that, for purposes of the statistical analysis, the second order axis in the heterogeneous dynamics groups was arbitrarily re-labeled as the "vertical" axis (in reality, the second order axis was the vertical axis for only half of the subjects). Thus, this main effect means that heterogeneous dynamics subjects were more likely to be biased toward the second order axis if controls were separated rather than integrated.

Apparently, subjects spent the majority of their time controlling both axes simultaneously. But the data suggest that heterogeneous subjects frequently stopped controlling the first order

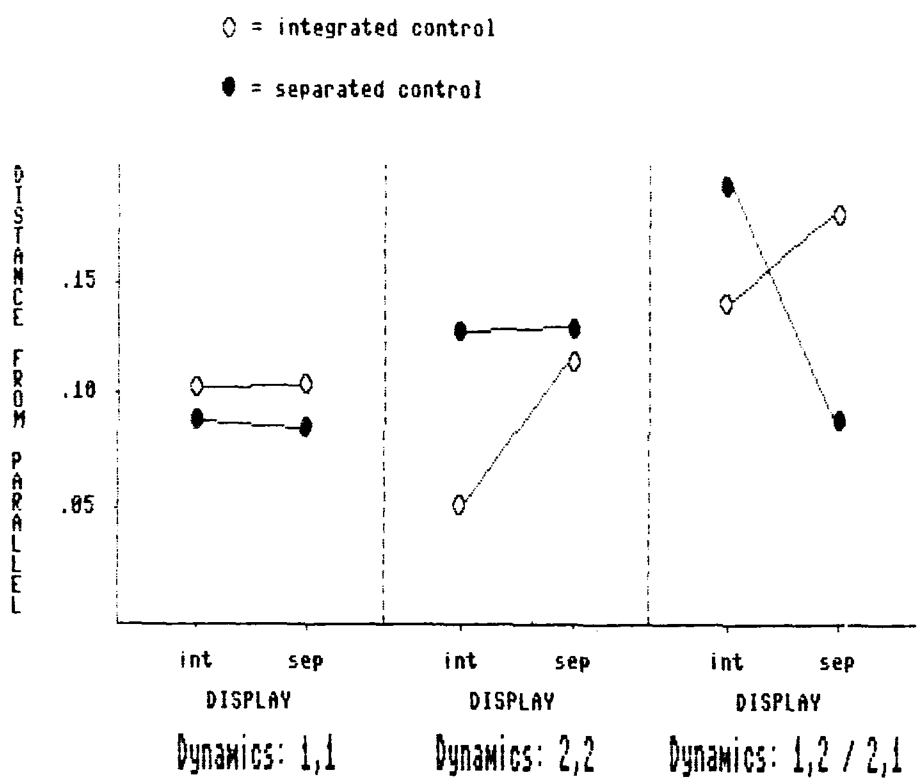

Figure 19. Distance of subjects' response strategies from simultaneous control in each of the 12 experimental conditions. These Euclidian distance measures are less than but monotonically related to the percent of time subjects spent alternating control between the vertical and horizontal axes.

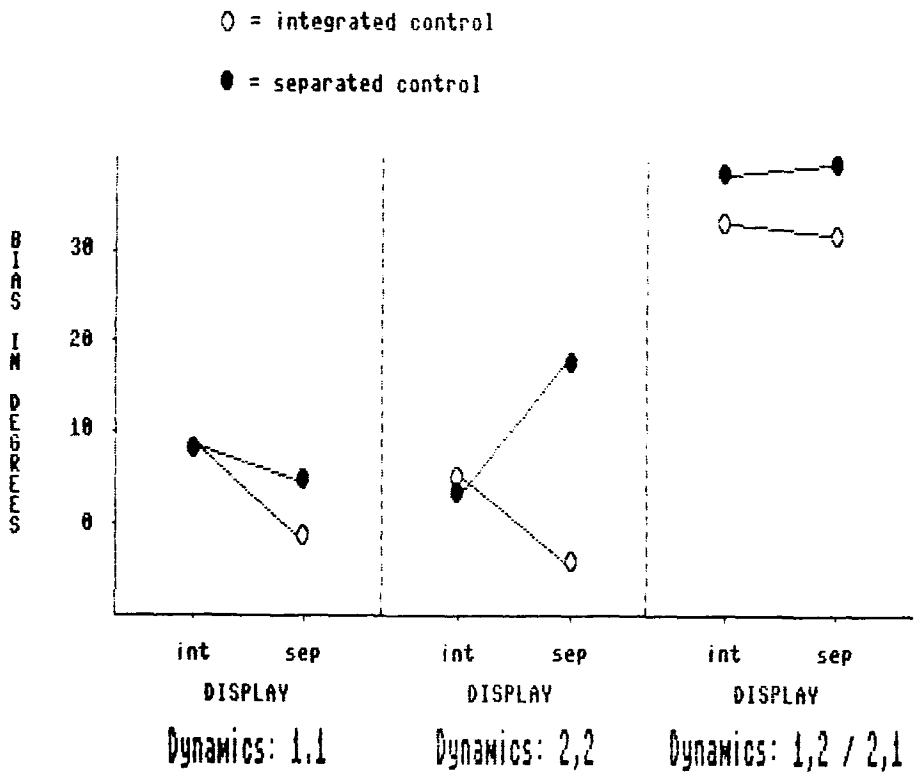

Figure 20. Biases of subjects' control strategies toward one axis or the other. The bias measure can range from -45 to +45 degrees. In the two left-most panels, a positive bias means that subjects controlled in the vertical axis more than in the horizontal axis. In the far right-hand panel, a positive bias means that subjects controlled in the second order axis more than in the first order axis.

axis in order to control the second order axis alone. In contrast, when homogeneous subjects adopted serial control, they divided their time equally between the vertical and horizontal axes.

Summary of Results

The present study was designed to evaluate the impact of display integrality, control integrality, and heterogeneity of control dynamics on dual axis tracking performance. All three variables influenced performance. Following is a summary of the major findings.

First, there was a major effect of the order on a paired axis: second order tracking consistently increased the error on the axis with which it was paired. This effect appears to be an effect of the demand of second order tracking, not of the heterogeneity of dynamics.

Second, in keeping with the demand effect, subjects decreased their control velocity and control gain when the dynamics on the other axis were second rather than first order. This effect was observed in both first and second order control. In addition, the response strategy measures showed that homogeneous control subjects were not biased to control either axis over the other, while heterogeneous control subjects were strongly biased to control the second order axis over the less demanding first order axis.

Third, overlaid on this effect of dynamics was an interaction with display integrality. When tracking dynamics were homogeneous, integrated displays led to less tracking error than did separated displays; but when dynamics were heterogeneous, display integrality had no effect. This particular interaction was not evident in any of the other response measures.

Fourth, although not evident in the error data, a compatibility of integrality effect appeared in both control velocity and effective time delay decrements. Statistical analysis of this effect showed that the effect manifested itself differently in the two control orders. When there were mismatches between the integrality of displays and controls, subject's second order effective time delay increased and their first order control velocity decreased, both symptoms of less effective tracking performance.

Fifth, when first order tracking was shared with second order tracking, the presence of the second order axis steepened the gain slope and but did not reliably raise the phase intercept of the subjects' first order response. Thus, the presence of second order dynamics on one axis influenced subjects' response to the first order axis, but it is not clear whether that influence modified the order of subjects' response.

Finally, integrated controls led to greater primary cross-coherence (confusions between axes) than did separated controls, and integrated displays led to greater secondary cross-coherence (confusions between control sticks) than did separated displays.

DISCUSSION

The present study had two goals. One was to examine how the integrality of displays and controls interact with each other and with the heterogeneity of control dynamics to shape dual axis tracking performance. The other goal was to place this interaction into some theoretical context that would facilitate generalization to manual control tasks such as exist in aviation. Three theoretical approaches were considered as potential components of whatever framework might finally emerge: resource theory, confusions theory, and Wickens' (1986c) compatibility of proximity hypothesis.

The outcome of the present experiment with respect to these two goals is summarized in Figure 21. This figure represents a theoretical framework incorporating resources, confusions, and the compatibility of proximity. Arrows indicate main or interaction effects of the three manipulations in the center on the inferred processing mechanisms in the columns. As the figure suggests, resource and confusions theory together account for the costs associated with the various experimental manipulations while compatibility of proximity describes the benefits.

Contrary to the claims of Navon (1985; Navon & Miller, 1986), the data show a dissociation of confusions from demand effects which suggests that the two are quite different things. On one hand, confusions (that is, primary and secondary cross-coherence) were greater when controls or displays were integrated rather than separated. But on the other, tracking error increased with separated--not integrated--displays, and the bandwidth of stable second order tracking (related to gain slope) decreased with separated, not integrated, controls.

Further, although confusions are apparent in the primary and secondary cross-coherence measures, resource demand and the compatibility of proximity seem to account for the major experimental effects. First, in keeping with resource theory, heterogeneity of control dynamics *per se* had no effect on performance; rather, tracking under both first and second order dynamics benefited if the dynamics on the other axis were first order and suffered if they were second order. Second, consistent with the compatibility of proximity hypothesis, dual axis tracking suffered given separated displays if the control dynamics on the two axes were the same but not if they were different. Third, a compatibility of integrality effect appeared in which performance benefitted when the integrality of displays and controls matched but suffered when they did not match. These effects were not generally accompanied by changes in confusions. Nevertheless, beyond these three effects, confusions were evident when integrated rather than separated displays and controls were used. These findings will now be discussed in turn.

Heterogeneity of Control Dynamics

Evidently, the improvement in second order tracking error under heterogeneous dynamics is attributable to the fact that first order

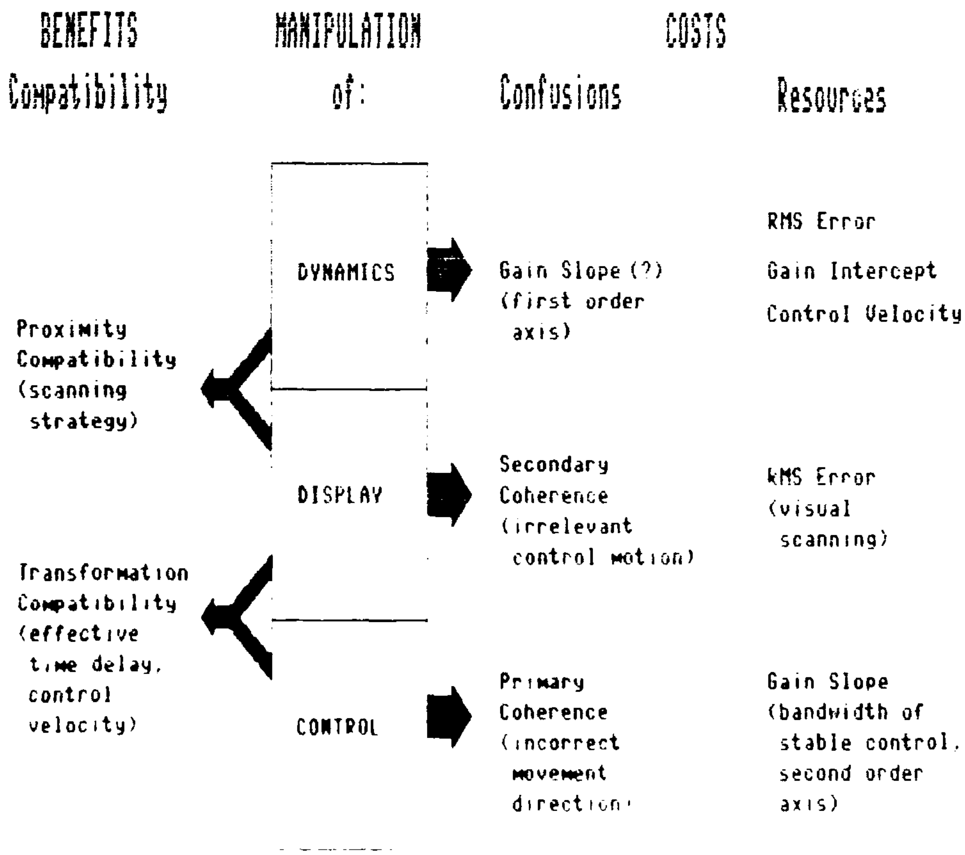

Figure [illegible] A model of the relation of confusions, resource competition, and compatibility to the experimental manipulations of the present study. See the text for a further explanation.

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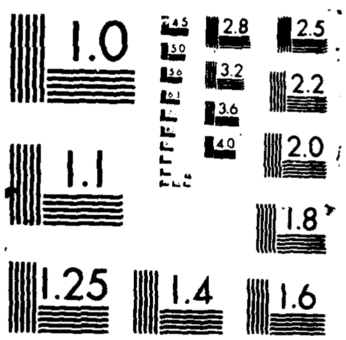
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dynamics are simply less demanding than second order dynamics. Thus, when first rather than second order dynamics are on one axis, there are more resources available for tracking on the other axis. The greater availability of resources then always led to a reduction in tracking error. This single principle then easily accounts for the increase in first order error and the decrease in second order error under heterogeneous compared to homogeneous control dynamics.

As was indicated in the introduction, people may become more cautious or may reduce their control effort when their processing resources are overtaxed. In a tracking task, this increased conservatism may then lead people to attenuate their control activity, as evidenced in control gain and control velocity (Wickens, 1976; Wickens & Gopher, 1977). In the present experiment, whenever the dynamics on one axis were second order, subjects attenuated their control gain and velocity on the other axis. But when first order dynamics were on one axis, the attenuation of gain and velocity on the other axis was considerably less. These results are consonant with other studies likewise showing gain attenuation under increased resource demand (e.g., Baty, 1971; Damos & Wickens, 1980; Damos & Lintern, 1982; Levison, Elkind, & Ward, 1971; Wickens, 1976; Wickens & Gopher, 1977). If control order confusions had been predominant, this is not the pattern that should have been observed. Rather, gain and control velocity should have always been attenuated under heterogeneous dynamics to a greater extent than under homogeneous dynamics.

Further evidence for a demand interpretation of the heterogeneity data appears in the results of the response strategy analysis. That analysis showed that while homogeneous subjects tended to control both axes to the same degree, heterogeneous subjects were more likely to concentrate primarily on the second order axis. In addition, many of the 32 subjects in the heterogeneous dynamics groups commented that they had tried to concentrate on the second order axis while occasionally checking to ensure that first order error was "acceptable" (more is said about this strategy in the next section). Thus, it appears that the greater difficulty of minimizing second order error led heterogeneous control subjects to allocate most of their attention to the second order axis.

This attention allocation strategy may explain the increase in first order gain slope under heterogeneous control dynamics. The increase in slope would have resulted if heterogeneous subjects selectively attenuated the gain of their response to the lower input frequencies while responding mainly to the higher, more salient input frequencies. If they were attending mainly to the second order axis and only occasionally controlling the first order axis, then the outcome of responding mainly to the higher first order frequencies would seem to be likely. In addition, this attentional strategy would also account for the absence of a corresponding increase in the subjects' phase intercept (that should have resulted if control order confusions were present), and for the absence of any effect in the second order axis. Thus, even the steeper first order gain slope under heterogeneous dynamics may provide evidence for a demand interpretation of the heterogeneity data rather than for control order confusions (although the latter interpretation can not be ruled out with certainty).

Display Integrality and the Heterogeneity of Dynamics

Wickens' (1986c) compatibility of proximity hypothesis predicts the interaction between display integrality and dynamics heterogeneity apparent in Figures 5 and 6. According to Wickens' hypothesis, tracking under heterogeneous dynamics should benefit from separated rather than integrated displays. In the present context, this benefit could have arisen either because separated displays helped subjects to avoid control order confusions (cf., Chernikoff & Lemay, 1963) or because the biased control strategy associated with heterogeneous dynamics was easier to carry out with separated displays. The main difficulty with the hypothesis that separated displays attenuated control order confusions is that there is no reliable evidence for a display effect in the gain slope data (see Figures 13 and 14) where such an effect would have to be found. Evidence concerning whether separated displays may have facilitated a biased control strategy is presented next.

To see how the biased control strategy of subjects in the heterogeneous dynamics conditions (depicted in Figure 20) may account for the above interaction, first consider those subjects in the homogeneous dynamics conditions. If it is assumed that control strategy biases are directly related to attentional biases, then it can be said that these subjects were unbiased and so allocated attention equally between the two axes. Thus, they attended equally to both vertical and horizontal errors even when displays were separated. Because separated error displays required some degree of visual scanning, the increase in tracking error associated with such scanning is evident for these subjects in the left panels of Figures 5 and 6 (cf., Allen, Clement, & Jex, 1970; Baty, 1971; Levison & Elkind, 1967; Levison, Elkind, & Ward, 1971).

Now consider subjects in the heterogeneous dynamics conditions. As seen in the strategy bias data, these subjects do not appear to have attended equally to both errors (again, assuming that response bias is directly related to attentional bias). In unsystematic self-reports, many of these subjects claimed to have used the following strategy. First, these subjects began a trial by reducing the first order error to some subjectively acceptable level. Because the disturbance signal was a sum of sinusoids, first order error would then remain "acceptable" in the absence of further control activity. Examination of the time series data for these subjects showed that they accomplished this goal in the first 2 or 3 seconds of the trial. Then, according to their self-report, these subjects focused their attention on the second order cursor for the remainder of the 120 second trial while occassionally checking the magnitude of first order error via peripheral vision. If first order error seemed to be growing "too large", then these subjects would initiate corrective control actions while continuing to focus mainly on the second order error.

One difficulty with the interpretation based upon these self reports is that the strategy data displayed in Figure 19 indicate that heterogeneous subjects may have controlled in both axes simultaneously at least 80 percent of the time. This apparent contradiction may have arisen from the conservative criterion used to decide when subjects were not controlling in an axis (i.e., no deflection of the appropriate control stick). For many subjects, this conservative criterion may have underestimated the time they actually spent controlling just one axis at a time, and overestimated the time controlling both axes in parallel.

If heterogeneous subjects given separated displays adopted the foregoing attentional strategy, then they clearly engaged in little if any visual scanning. Thus, the scanning cost present under homogeneous dynamics would be absent under heterogeneous dynamics. This is precisely the effect seen in Figures 5 and 6. But the compatibility of proximity hypothesis also requires that integrated displays inhibit the biased control strategy. From Figure 20, it is clear that display integrality had no effect whatever on control bias. Further, no systematic effect of display integrality on heterogeneous tracking error is apparent in the right panels of Figures 5 and 6. The question then is whether control bias itself is sufficient to account for the display by dynamics heterogeneity interaction with out reference to the compatibility of proximity hypothesis. From the present data, the answer to this question appears to be "yes". Yet the interaction is predicted by the compatibility hypothesis and is in agreement with a large body of other data also pointing to the compatibility hypothesis (see Wickens, 1986c, for a review).

One might say, therefore, that the present data support compatibility of proximity as an intervening variable but not as a hypothetical construct (MacCorquadale & Meehl, 1948; Gopher, 1986). An intervening variable is a convenient label given to a class of experimental procedures and the set of outcomes to which they consistently give rise. Thus, compatibility of proximity as an intervening variable integrates the present data into the large body of other data that is subsumed under the hypothesis. On the other hand, a hypothetical construct refers to an internal psychological process that in some sense is independent of the experimental manipulations used to detect it. It is compatibility as a hypothetical construct that seems unnecessary to account for the present data.

One possible objection to the "strategy without compatibility" account of the display by dynamics heterogeneity interaction is that it implies psychological equivalence of the integrated and separated displays under heterogeneous dynamics. Equivalence, in turn, implies that display integrality was completely irrelevant under heterogeneous dynamics. If this were in fact the case, then there could be no display effects of any kind with respect to any independent variable under heterogeneous dynamics. This implication is clearly wrong, however, because there were effects involving display integrality that remained reliable under heterogeneous control dynamics. These effects were evident in the control velocity, effective time delay, and secondary cross-coherence measures (and are discussed in the next two sections). But this objection can be answered by noting that a biased attentional strategy need only have attenuated the psychological difference between displays. If this attenuation was sufficient to render display integrality irrelevant with respect to tracking error but not with respect to some other dependent measures, then the present set of results are consistent with the "strategy without compatibility" hypothesis.

Finally, interpretation of the display by dynamics heterogeneity manipulation as a strategy effect should raise a caution that heretofore has not been recognized. Chernikoff and Lemay (1963) found exactly the same interaction and took it to mean that separated displays helped subjects to avoid such confusions. Other writers have echoed that interpretation, suggesting that it may be a useful principle of display design (see Wickens, 1984a, 1987a,b for reviews). But if the strategy interpretation is correct, then Chernikoff and Lemay's conclusions are misleading at best--and could be dangerous under the right circumstances. While the strategy of allocating attention primarily to just one of the two tracking axes may be viable in the laboratory where the inputs are sinusoidal, it could be fatal in a high-speed aircraft. This makes it seem unlikely that pilots, for example, would actually employ such a strategy. Consequently, the finding of no penalty to separated displays under heterogeneous dynamics may have little generality beyond the safety of the laboratory.

An implication of the foregoing strategy interpretation is that integrated displays lead to less tracking error than do separated displays as long as attention is allocated equally to both tracking axes. Yet integrated displays also appear to lead to more confusions between control sticks (secondary cross-coherence). This result parallels a similar finding with respect to control integrality and confusions between axes. How these findings may be understood is discussed in the next section.

Control Integrality

Unlike many studies (Baty,1971; Bartram et al., 1985; Levison et al., 1971; Regan, 1960), the present study found that tracking error was unaffected by control integrality. Importantly, the superiority of separated controls with heterogeneous dynamics reported by Chernikoff and Lemay (1963) is completely absent. Why control integrality had no effect on error in the present study is not known. With respect to the Chernikoff and Lemay study, one possibility is that the difference between the first and second order dynamics used in the present experiment is less than that between the zero and second order dynamics used by Chernikoff and Lemay; thus, a compatibility of proximity effect between control integrality and control dynamics may have been less likely in the present study. However, this difference does not account for the discrepancy with the other studies just cited which did not use heterogeneous control dynamics but found a consistent cost to separated controls. One important difference between the present experiment and those other studies is the experimental design used. While those studies manipulated control integrality within subjects, the present experiment did so between subjects.

Perhaps the influence of control integrality on tracking error in within-subjects designs is mediated by what might be called a "contrast effect". That is, a decrease in tracking error associated with integrated controls may not result from the fact that the control is integrated per se, but from the subject's perception that tracking seems easiest with the integrated rather than the separated controls. This perception, in turn, might then lead to a "self-fulfilling prophecy" in which subjects expect to perform more poorly with separated controls and therefore do perform more poorly.

Whether such a contrast effect occurred in the cited experiments is another question, but the fact that the possibility can not be ruled out is one of the hazards of a within-subjects design (cf., Matthews, 1986; Poulton, 1974, 1982). If a contrast effect was operating in those earlier studies, then the present data may present a more accurate picture of the effect of control integrality on tracking error. Future research may be able to clarify this picture by specifically comparing the performance of subjects who track under both control integrality conditions with subjects who track under just one integrality condition.

While tracking error was not influenced by control integrality, confusions were affected. Just as display integrality led to more control stick confusions (secondary cross-coherence) than did separated displays, so integrated controls led to more axis confusions (primary cross-coherence) than did separated controls. Confusions thus appear to be most likely when signals are transmitted via a common channel; in this case, a common control hand. Navon and Miller (in press) suggest the metaphor of two telephone lines that have become crossed. In terms of this metaphor, it seems that the probability of crossed lines is significantly diminished when the lines travel through separate rather than common cables.

As is evident, these confusions did not lead to greater tracking error. Nor do they appear to have had any other deleterious effects on subjects' tracking performance. Indeed, the optimality of subject's second order transfer function (as indexed by gain slope, a determinant of the bandwidth of stable control) appears to have improved with an integrated control in spite of the attendant confusions. This fact, coupled with the superiority of tracking with integrated displays, suggests that confusions generally may not be able to account for task decrements in at least some task paradigms as Navon (1985; Navon & Miller, in press) has claimed.

This dissociation between confusions and other measures suggests that the two reflect different underlying processes. Confusions may represent cross-talk between signals (cf., Wickens, 1987b) while error and open loop gain may mainly reflect competition for scarce resources.

Control and Display Compatibility

An important interaction was found between the integrality of displays and controls. This interaction was of the form suggested by Baty (1971); that is, tracking benefitted when controls and displays were both integrated or both separated, but suffered when one was integrated and the other was separated. Significantly, this effect was absent in the error data, appearing only in the control velocity and effective time delay measures. This result may suggest either that the compatibility of integrality principle is not of great practical importance in dual axis tracking, or that it may be important only under higher levels of demand or stress than were used here.

Nevertheless, the theoretical implications of the effect seem to be significant. First, the fact that effective time delay increased with mismatches of display-control integrality supports the hypothesis that subjects needed to perform some kind of cognitive transformation of the error display under such circumstances. In the introduction, these transformations were called "mapping operations". Since effective time delay under incompatible display-control configurations averaged about 130 ms longer than under compatible configurations, this figure may be taken as an estimate of the duration of such mapping operations (see Pachella, 1974, for the restrictive assumptions underlying subtractive logic).

Second, the cross-coherence data gave little evidence of the compatibility effect. Confusions between control sticks (secondary cross-coherence) were greater with integrated rather than separated displays as would be expected assuming occasional failures of the mapping operations (cf., Garner, 1974; Garner & Fefoldy, 1970). But confusions between which signals went to which axes (primary cross-coherence) were unaffected by display integrality; rather, such confusions were consistently greater with integrated rather than separated controls. Thus, confusions due to mapping failures appear to have been rare.

Third, because the compatibility effect was evident in the display by control integrality interaction in the control velocity data, the underlying mapping operations may be resource consuming. Attenuated dual axis control velocity (relative to single axis tracking) may suggest that subjects have grown more cautious, a response consistent with increased resource demand (Baty, 1971; Damos & Wickens, 1980; Damos & Lintern, 1982; Levison, Elkind, & Ward, 1971; Wickens, 1976; Wickens & Gopher, 1977). If so, then one would also expect a corresponding decrease in control gain. Since such a decrease in gain was not found, the demand of these operations for resources may be slight. This slight demand combined with the rarity of confusions attributable to mapping failure may explain why the compatibility of integrality effect was absent in the tracking error data.

Re-evaluation of Chernikoff and Lemay (1963)

Chernikoff and Lemay's (1963) data have generally been cited as evidence for the important role of confusions in dual axis tracking (e.g., Levison & Elkind, 1967; Wickens, 1984a, 1987b). The present results suggest that the significance of those early data need to be reconsidered. As mentioned above, their finding that the scanning cost associated with separated displays disappeared under heterogeneous control dynamics appears to be reliable. But it also appears to result from the strategy subjects adopt to perform the task, not from control order confusions that are somehow alleviated by separated displays.

As indicated earlier, another one of Chernikoff and Lemay's findings appears to have been less robust; namely, their finding that tracking error under heterogeneous dynamics was greater with integrated rather than separated controls. Although the present control integrality interaction effect was in the "right direction" in the first order axis, the effect was in the opposite direction in the second order axis and was unreliable in both cases. One may speculate that the discrepancy between experiments arose because, as was pointed out earlier, the difference between the zero and second order dynamics used by Chernikoff and Lemay is greater than that between the first and second order dynamics used here. A direct comparison between both pairs of control orders will be needed to finally resolve this issue. In the absence of such a direct comparison, one can not dismiss the possibility that the statistical significance of the effect in Chernikoff and Lemay's experiment is due to a type 1 error, some sort of contrast effect, or an improperly balanced design. At the present time, therefore, the present data remain inconclusive as to whether control integrality interacts with dynamics heterogeneity in any systematic way.

If Chernikoff and Lemay's data are distorted by the unbalanced within-subjects design which they used, then any attempt to interpret any of their findings seriously is bound to be risky. But it is tempting to speculate as to why they found tracking error to be greatest under heterogeneous dynamics for both zero and second order axes. As noted in the introduction, Chernikoff and Lemay used simple disturbance inputs whose patterns could have been easily learned. Under these circumstances, it is conceivable that highly practiced subjects may have progressed to a pre-cognitive mode of tracking that could be likened to automatic processing (Krendel & McRuer, 1968; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977; Schneider, 1984; Wickens, 1984a). If so, then resource demand should have become minimal with the result that no demand effects were possible. In some sense, this absence of resource competition between tracking axes may have created a "noise-free" environment in which to look for evidence of control order confusions in tracking error.

Given this perspective, Chernikoff and Lemay's heterogeneity data can be reconciled with the present findings. Specifically, the demand effect of the present experiment can be added to the heterogeneity effect of the Chernikoff and Lemay study. If the demand effect is sufficiently large compared to the heterogeneity effect, then the latter will be masked by the former. Additional research will be needed to evaluate this possibility.

Perception of Structure: An Alternative to Resources and Confusions

The focus of this paper has been on resource competition and confusions in dual axis tracking. But the discussion would not be complete without acknowledging Lintern's (in preparation) recently proposed alternative to attention-based accounts of complex task performance. Writing from the perspective of ecological psychology (e.g., Gibson, 1979), he suggests that performance decrements arise from poorly learned task structures. For example, subjects may easily learn the pattern of a tracking disturbance function made up of just one sinusoid. But if a second task somehow distracts subjects from attending to the tracking task, then they may not discover the pattern as quickly as otherwise. As will be seen, Lintern's hypothesis can account for certain features of the present data but seems unable to account for the data in its entirety.

In the present study, subjects were presented with random appearing disturbance functions so that there was no obvious pattern to be discovered. But this does not mean that the task lacked structure. Rather than residing in the disturbance function, task structure resided in the control dynamics of each axis. That is, the control dynamics constrained how subjects could successfully perform the task. If subjects discovered the nature of those dynamics, then they could generate the appropriate kinds of control actions to reduce tracking error; if they did not, then tracking errors would be large.

According to this "discovery of structure" hypothesis, subjects in the heterogeneous control conditions should have had greater difficulty than those in homogeneous conditions in learning the control dynamics appropriate to each axis. This is because subjects can not learn the dynamics on one axis while attending to another axis having different dynamics. But if, as in the homogeneous conditions, the dynamics are the same on both axes, then subjects will always learn something about the dynamics on both axes no matter to which axis they happen to attend.

Since heterogeneous subjects appear to have attended more to the second order rather than to the first order axis, these considerations suggest that the first order dynamics should have been learned less well than the second order dynamics. One way to gauge such learning is by examining the optimality of subject's single axis open loop describing functions. Optimality is defined here with respect to the response needed to make the human-plant combination behave as a first order system. Thus, the optimal human open loop response to a first order system is a zero order response with a gain slope of zero dB per decade and a phase intercept of zero degrees. Likewise, the optimal response to a second order system is a minus-first order response with a gain slope of 20 dB per decade and phase intercept of 90 degrees. The fact that heterogeneous and homogeneous dynamics subjects differed with respect to the optimality of the single task first order response but not the second order response seems consistent with the discovery of structure hypothesis.

Whether the other major findings of the present experiment could also be handled by the discovery of structure hypothesis is unclear, but it seems unlikely. How, for example, would the hypothesis explain the axis confusions associated with integrated controls or the control stick confusions associated with separated displays? Nevertheless, the perception of structure may be one of several important process needed to fully account for dual axis tracking performance.

Summary

The present study had two goals. One was to examine how the integrality of displays and controls interact with each other and with the heterogeneity of control dynamics to shape dual axis tracking performance. The other goal was to place this interaction into some theoretical context that would facilitate generalization to manual control tasks such as exist in aviation. Three major theoretical frameworks were considered: resource theory, confusions theory, and Wickens' (1986c) compatibility of proximity hypothesis.

As Figure 21 suggests, resource and confusion theory together account for the costs associated with the various experimental manipulations while compatibility of proximity describes the benefits. In addition, the figure identifies the particular dependent measures in which the costs and benefits of the various experimental manipulations were evident.

In general, the experimental results and their interpretation are clear. First, there does not appear to be a cost to dynamics heterogeneity *per se*, although weak evidence for control order confusions may have been observed in the first order axis. Rather, tracking error seems to increase primarily as a function of the summed difficulty or resource demand of the dynamics on the two axes. This interpetation in terms of resource demand was supported by appropriate changes in subjects' control activity as indexed by their open loop control gain and control velocity.

Second, while display and control integrality both led to confusions (secondary and primary cross-coherence), those confusions did not lead to increased tracking error nor to attenuated open loop gain. If anything, confusions were associated with improvements in other measures of tracking performance suggesting that different processes underlie the different measures.

Third, separated displays led to greater tracking error, presumably because of the visual scanning requirements involved. While such a scanning cost was absent if heterogeneous control dynamics were used, this absence appears to have resulted from subject attentional allocation strategies rather than from dynamics heterogeneity itself. Nevertheless, the resulting display by dynamics heterogeneity interaction is empirically consistent with the compatibility of proximity hypothesis if compatibility is understood as an intervening variable rather than a hypothetical construct. Yet, because the underlying allocation strategy may be specific to the laboratory tracking task, it may be safest to assume that integrated displays will lead to less error in most "real world" tasks regardless of control heterogeneity.

Fourth, there appears to be a compatibility of integrality principle in which dual axis tracking performance benefits if displays and controls are both integrated or both separated but suffers if one is integrated and the other is separated. This principle may be viewed as a special case of the compatibility of proximity. For most applications, then, the critical question may not be whether displays or controls are integrated but whether the configurations of the two match.

These results encourage a view that resource theory, confusions theory, and the compatibility of proximity hypothesis each contribute something different to an overall understanding of complex task performance. The data show a clear dissociation between documented confusions and most other measures of performance. Resource theory presents a coherent account of the heterogeneity of dynamics manipulation. Confusions theory seems able to account for the main effects of control and display integrality. Compatibility of proximity seems to account for the interaction between displays and controls.

Future research may be able to extend the documentation of confusions and compatibility effects to tasks other than dual axis tracking. If so, and if these processes can be distinguished from demand effects, then the prognosis for a general theory of complex task performance may be promising.

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VITA

Martin Lee Fracker was born on June 17, 1953, in Seattle, Washington. Following his graduation from Chief Sealth High School (Seattle) in 1971, Martin attended college at LeTourneau College in Longview, Texas, for one year and then transferred to Seattle Pacific University in Seattle. He graduated magna cum laude from Seattle Pacific in 1977 with a double major in Theater Arts and Psychology. In the fall of 1977, Martin entered the Master of Science program in Psychology at Western Washington University, Bellingham, Washington. During the following summer, Martin entered the United States Air Force as a reserve (active duty) second lieutenant. With the assistance of the Air Force, Martin completed the Master of Science degree at Western in 1981.

While working on his master's degree, Martin was assigned to the Sheppard Technical Training Center, Sheppard Air Force Base, Texas, where he advised the Center commander on the applications of psychological research to training technology. As a result of his work at Sheppard, Martin was promoted to captain, granted a Regular commission, and awarded the Air Force Commendation Medal.

In late 1981, Martin was reassigned to the Occupational Measurement Center, Randolph Air Force Base, Texas. As an occupational analyst Martin conducted several studies of airmen career fields in order to evaluate how well they were organized and how effectively they trained their personnel. One of these studies led to a high level meeting at United States Air Force Headquarters, Washington, D. C., at which Martin was the principal presenter. One outcome of this meeting was a major restructuring of one of the largest career fields in the Air Force. As a result of this and other achievements, Martin was awarded the Meritorious Service Medal and selected to enter the University of Illinois doctoral program in Psychology at Air Force expense.

Martin began his doctoral studies at the University of Illinois in 1984 and graduated in 1987. His achievements during those three years led to membership in the national Honor Society of Phi Kappa Phi. In 1986, the Armstrong Aerospace Medical Research Laboratory at Wright-Patterson Air Force Base, Ohio, issued a "by name" request for Martin based on the recommendation of his academic advisor. In early 1987, this request was granted by the Air Force, and Martin was transferred to the Laboratory following completion of his doctorate.

<u>Publications</u>

Fracker, M. L., & Wickens, C. D. (1987). Resources, confusions, and compatibility in dual axis tracking: Displays, controls, and dynamics. In E. L. Weiner (Ed.), <u>Proceedings of the 31st annual meeting of the Human Factors Society</u>. Santa Monica, CA: Human Factors Society.

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